REPORT 1388

NACA RESEARCH ON SLURRY FUELS

By M. L. Pinns, W. T. Olson, H. C. Barnett, and R. Breitwieser

SUMMARY

An extensive program was conducted to investigate the use of concentrated slurries of boron and magnesium in liquid hydrocarbon as fuels for afterburners and ramjet engines. Analytical calculations indicated that magnesium fuel would give greater thrust and that boron fuel would give greater range than are obtainable from jet hydrocarbon fuel alone. It was hoped that the use of these solid elements in slurry form would permit the improvement to be obtained without requiring unconventional fuel systems or combustors.

Slurries consisting of 50 percent or more magnesium or boron in JP fuels were prepared, although it was difficult to obtain successive batches with uniform properties. A vaporization process was devised for the preparation of very finely divided magnesium. The storage stability, spray characteristics, and non-Newtonian flow behavior of the slurries varied with the particle size of the metal and the type and concentration of the additives incorporated. The storage stability was limited to 6 months or less, but some types of magnesium slurries could readily be reconstituted by mixing. Slurry fuels formed coarser sprays than jet hydrocarbon fuel did.

Tests in pipe-connected combustors of various designs showed that slurried magnesium burned very readily even under conditions where jet hydrocarbon fuel itself would not burn, and the expected improvement in thrust was obtained. Data from tests on afterburners indicated that coolant injection would accentuate the improvement. However, some modification of conventional fuel systems and combustors was required to compensate for the difference in flow properties between jet hydrocarbon and slurry fuels.

Small ramjet vehicles fueled with magnesium slurry were flown successfully, but the test flights indicated that further improvement of combustors and fuel systems was needed.

In contrast to the favorable results with magnesium slurries, the boron slurries that were prepared were more difficult to burn than conventional jet fuel and formed objectionable deposits in the combustor.

INTRODUCTION

This report summarizes the NACA research program on slurry fuels that was conducted from 1947 to 1957. Since it encompasses about forty NACA Research Memorandums (see reference list), which represent the work of many individuals, this report presents only the highlights of those memorandums.

The slurry fuels considered herein are suspensions of metals in hydrocarbons. For flight propulsion, certain metals as fuels offer the possibilities of more flight range or more thrust

than can be obtained with conventional hydrocarbons. They may also provide combustion under operating conditions where hydrocarbons alone will not burn. A discussion of metals and their compounds as fuels and a review of experimental work on them by the NACA and others up to 1951 are presented in reference 1, and more recent reviews are presented in references 2 and 3. References 1 and 3 also consider the selection of particular fuels for the research effort. The reasons for interest in certain metals as fuels are reviewed here with the aid of four figures:

Figure 1 presents the heating values of a few selected fuels relative to JP-4 jet fuel as 1. Boron and a typical boron hydride, pentaborane, have more heating value on a weight basis than JP-4. Magnesium, aluminum, boron, and pentaborane all have greater heating values than JP-4 fuel on a volume basis. These fuels also have greater heating values per pound of air burned in stoichiometric mixtures.

Higher heating values on a weight and volume basis make longer flight range possible (ref. 4). Heating value per pound of air burned is indicative of the amount of thrust that can be obtained from an engine of a given size. However, because much of the heat of combustion may be used to volatilize and dissociate the combustion products, the heating value per pound of air cannot be used directly. The cross-hatched parts of the bars in figure 1 therefore indicate the relative net thrust that theoretically can be achieved after making appropriate corrections for these effects.
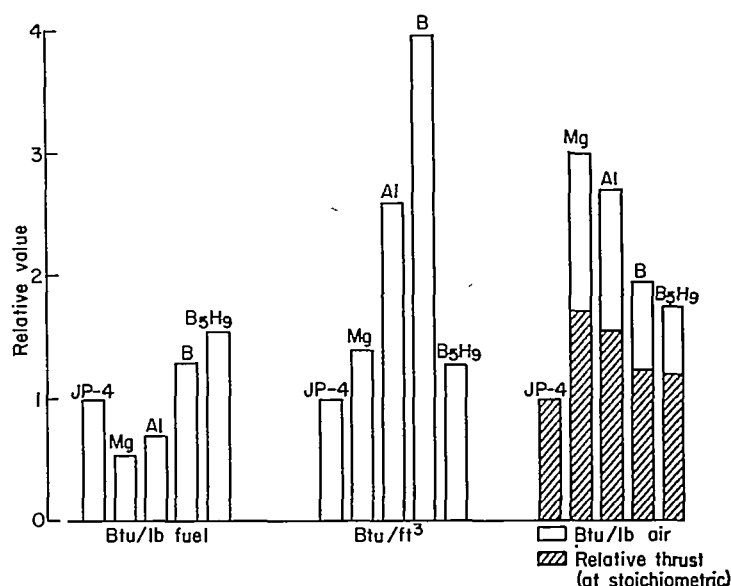

FIGURE 1.—Relative heating values (ref. 2).

Figure 2 is a plot of fuel-weight specific impulse against air specific impulse for a number of fuels (see also refs. 5 to 7). Air specific impulse, which is an index of thrust, is the number of pounds of total stream thrust per pound of airflow per second. Fuel-weight specific impulse, an index of fuel economy on a weight basis, is air specific impulse divided by fuel-air ratio. Because aluminum, boron, and magnesium burn at higher temperatures and at higher over-all fuel-air

ratios, they can give higher thrust per pound of air than is possible with hydrocarbon jet fuel. Up to an air specific impulse of 152 seconds, hydrogen, boron hydrides, and boron all require less fuel flow to maintain a given thrust than would jet fuel (represented in fig. 2 by octene-1) and hence would give increased flight range.

Figure 3 shows the relative flight range calculated for a ramjet-powered missile at 60,000 feet and Mach 3.2 following
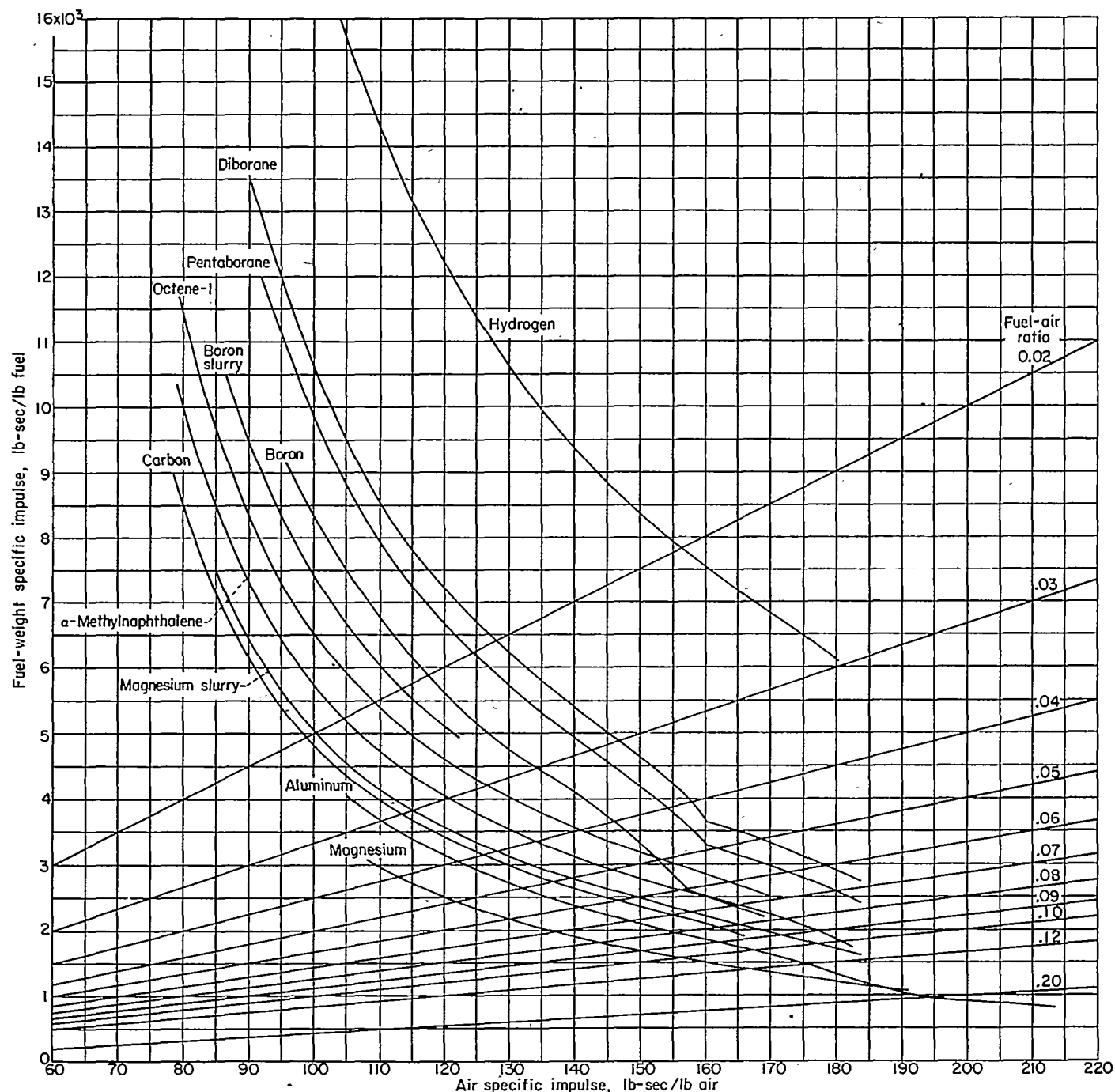

FIGURE 2.—Theoretical combustion performance of representative high-energy fuels. Slurry fuels, 50 percent metal by weight in octene-1. Combustor-inlet air temperature, 100° F; inlet air pressure, 2 atmospheres (ref. 7).
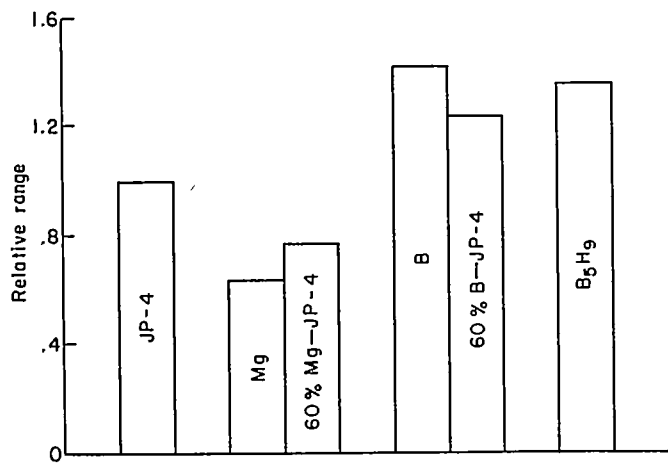
FIGURE 3.—Relative range of ramjet missile. Initial altitude, 60,000 feet; free-stream Mach number, 3.2; Breguet flight path (ref. 2).

a Breguet flight path (ref. 4). The reason for interest in boron is evident from this figure.

Figure 4 illustrates the advantages to be obtained from the high thrust possible with magnesium. A typical bomber was selected for illustrative purposes. With no thrust augmentation, the bomber did not take off even with many thousands of feet of runway. With 43-percent thrust augmentation from JP-4 fuel, the bomber takes off at 13,500 feet over a 10-foot obstacle. This distance is shortened to 10,700 feet at 67-percent thrust augmentation with a magnesium slurry. With 100-percent thrust augmentation with magnesium slurry and water injection combined, the takeoff distance over a 10-foot obstacle is about 8000 feet.

These, then, were the reasons for interest in metals as aircraft fuels. Long flight range is theoretically achievable with boron, while high thrust for afterburners or for ramjet engines might be obtained from aluminum, boron, or magnesium.

Since little or nothing was known regarding methods of combustion of metals in jet engines, it was first necessary to learn how to use these metals as aircraft fuels. The earliest NACA studies were based on the combustion of aluminum as wire or powder (ref. 8). The efforts of other organizations along analogous lines have been reviewed in reference 1.
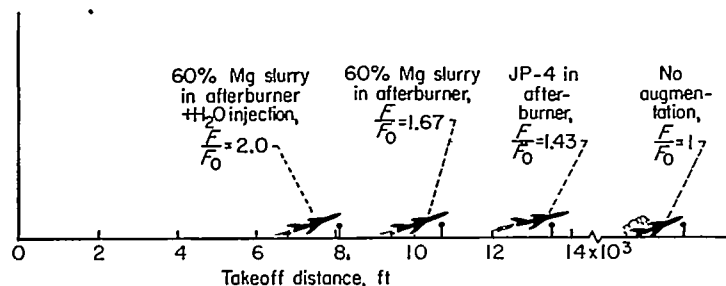
Aluminum was very early dropped from the program in favor of magnesium, because the sticky, molten aluminum oxide caused a very serious deposit problem in the combustor. Magnesium oxide does not melt appreciably at the flame temperature normally encountered and does not stick to the combustor walls as aluminum oxide does.

Handling difficulties indicated that slurries of metal powder in liquid hydrocarbon might be more satisfactory than the pure metal because they could probably be used without radical departure from conventional fuel systems and combustors. It then became necessary to learn how to prepare boron and magnesium slurries that would perform satisfactorily. The preparation of slurries, the study of their physical and combustion properties, and the development of combustors to burn slurries were conducted concurrently at the NACA Lewis laboratory.

SLURRY PROPERTIES DESIRED AND METHODS OF MEASUREMENT

OBJECTIVES

The objective in slurry preparation was to achieve a metal concentration of 50 percent or more (by weight) in JP-3, JP-4, or JP-5 (all three described in specification MIL-F-5624C) jet-engine hydrocarbon fuel in order to obtain a worthwhile increase in performance. It was necessary to achieve sufficient fluidity to permit flow and injection into more or less conventional jet-engine combustors and still maintain the slurry consistency at a sufficiently high level to prevent the suspended particles from settling too rapidly. Furthermore, as will be discussed later, it was desirable to use the most finely divided boron and magnesium available in order to obtain the best combustion characteristics. When the particles were relatively coarse, the suspension was relatively fluid, and it was necessary to thicken the hydrocarbon medium. When the particles were very fine, the mixture was a stiff mud unless a surface-active additive was used to promote wetting of the particles by the hydrocarbon. The quantity of metal that could be suspended and the properties of the suspension were functions of the particle shape and size distribution, the composition of the hydrocarbon medium, and the type and concentration of additives.

MEASUREMENT OF CHARACTERISTICS

Slurry fuels, like other concentrated suspensions, have non-Newtonian flow properties; that is, the rate at which they flow is not directly proportional to the force applied. The variable relation is conveniently measured with viscometers, several of which were used at various stages in the program. A modified Stormer viscometer (described in ref. 9) was used at rates of shear up to 1800 seconds^{-1}, and an automatic recording viscometer (described in ref. 10) was used over a wide range of rates of shear to obtain plots of rate of shear or rate of rotation of spindle against shearing stress or driving force.

FIGURE 4.—Takeoff characteristics of turbojet bomber over 10-foot obstacle (ref. 2). (F, augmented thrust; F_0, unaugmented thrust.)

Schematic diagrams of such plots shown in figure 5 represent various types of flow behavior. Figures 5 (b), (c), and (d) are idealized plots that only approximate the actual behavior of slurries. The arrows in the figures indicate that the curves were obtained by first continuously increasing the shearing stress (up-curve) and then continuously decreasing it (down-curve). The rate of shear of Newtonian materials varies linearly with the shearing stress, and the viscosity is proportional to the reciprocal of the slope of the plot (fig. 5 (a)). For plastic materials, a finite shearing stress must be applied before the rate of shear becomes a linear function of shearing stress (fig. 5 (b)). The plastic viscosity is measured by the reciprocal of the slope of the linear portion of the plot. The yield value is defined as the intercept of the extrapolated linear portion with the shearing stress axis (fig. 5 (b)). The rate of shear of pseudoplastic materials increases nonlinearly with shearing stress (fig. 5 (c)). When the shearing stress required to effect a given rate of shear decreases upon prolonged application of the stress, the material is thixotropic, and the up- and down-curves do not coincide (fig. 5 (d)). The apparent viscosity at any selected point on the flow curve is proportional to the reciprocal of the slope of a straight line drawn from that point to the origin, as in figures 5 (b) and (c).

Low plastic or apparent viscosity and low yield value
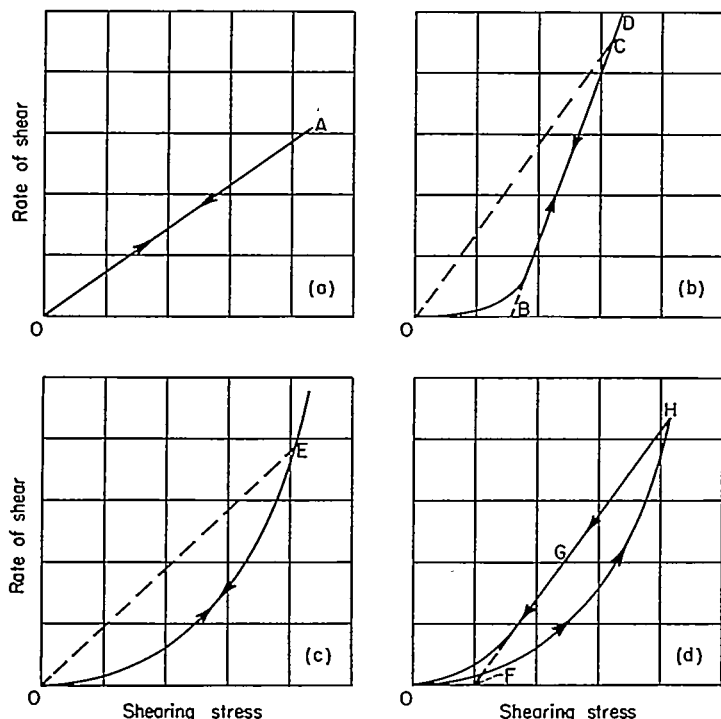
(a) Newtonian material: Viscosity=(Instrument constant)/(Slope of OA).

(b) Plastic material: Plastic viscosity=(Instrument constant)/(Slope of BCD); Yield value=Length OB along axis; Apparent viscosity= (Instrument constant)/(Slope of OC).

(c) Pseudoplastic material: Apparent viscosity=(Instrument constant)/(Slope of OE).

(d) Thixotropic material: Plastic viscosity=(Instrument constant)/ (Slope of FGH); Yield value=Length of OF along axis.

FIGURE 5.—Schematic plots of rate of shear against shearing stress. Arrows indicate path of increasing rate of shear followed by decreasing rate of shear.
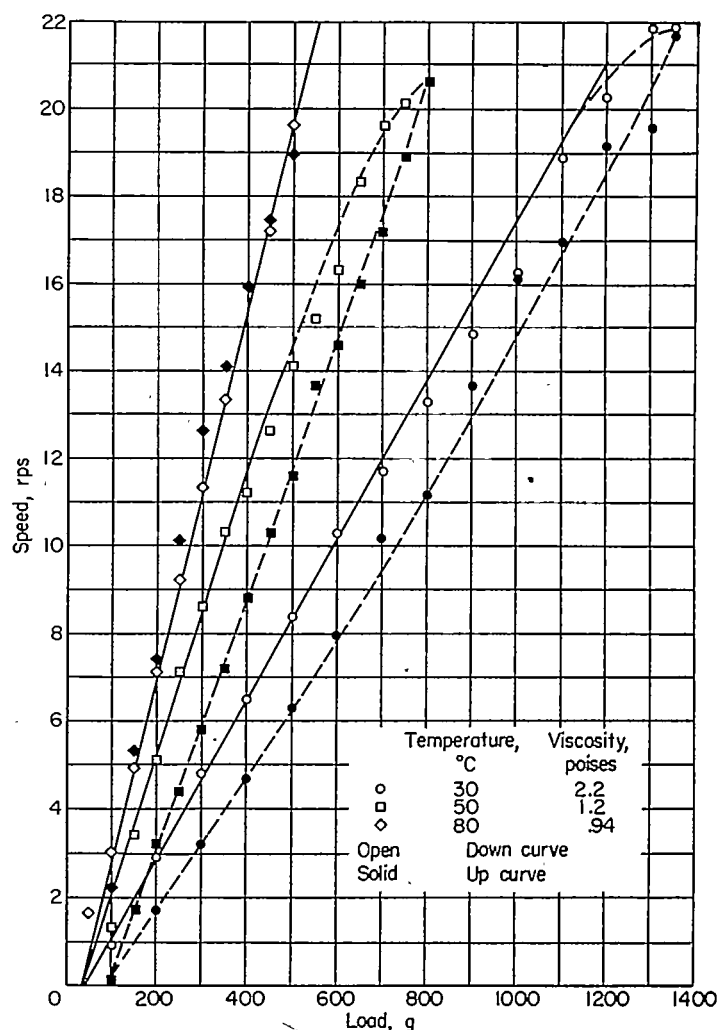

FIGURE 6.—Effect of temperature on curves obtained with Stormer viscometer one day after preparation of slurry containing 50 percent boron, 48.1 percent JP–5, 1.6 percent glyceryl sorbitan laurate, and 0.3 percent aluminum octoate (ref. 17).

facilitate the pumping of a slurry; while high levels of viscosity, yield value, and thixotropy retard the settling of the suspended particles.

Other viscometers used were the Severs Extrusion Rheometer at about 1000 to 24,000 seconds^{-1} and a Brookfield viscometer at about 0.5 and 10 seconds^{-1}. They are described in reference 11. The Brookfield instrument gave apparent viscosities that were very convenient comparative measurements. Unless otherwise indicated, all viscosity measurements were made at about 86° F.

Stability toward settling was commonly measured by observing sedimentation of the slurry in 50-milliliter graduated cylinders immersed in a water bath at 86° F. The extent of settling was then expressed as the settling ratio, defined as the ratio of depth of the sediment layer to the initial depth of slurry in the cylinder. Qualitative observations were also made of settling in larger containers.

The relative ease with which a settled slurry could be redispersed was estimated for some slurries by shaking under controlled conditions (described in ref. 11) the 50-milliliter cylinder of slurry used in the settling test. The "percent redispersible" was the percent of sediment layer that could be poured out after shaking.

Dielectric properties of boron and magnesium suspended in mineral oil were studied in order to learn about sedimentation, particle shapes, and particle agglomeration, and to form the basis for an instrumental method of estimating the concentration of metal in a suspension (refs. 12 to 14).

PREPARATION AND PROPERTIES OF BORON SLURRIES

BORON

The boron powder used in most of the work was a commercial product prepared by the thermal reduction of boric oxide with magnesium. Analysis of a large number of samples of this grade of boron showed that the purity ranged from 87 to 91 percent free boron. Among the known impurities were magnesium, boron oxide, moisture, and traces of acid. Average particle sizes ranged from approximately 0.6 to 1.4 microns, as determined by the air permeability method with a Fisher Sub-Sieve Sizer. Electron micrographs showed the particles to be irregularly shaped (ref. 15).

Another grade of boron, prepared by an electrochemical process, contained about 97 percent elemental boron and had an average particle diameter less than 1 micron.

METHOD OF PREPARATION OF BORON SLURRIES

The addition of the surface-active additive glyceryl sorbitan laurate and the gelling additive aluminum octoate was desirable in order to obtain satisfactory flow properties (ref. 15). Later experience suggests that other surface-active additives could have been used equally well. Of the various grades of aluminum octoate available, the one used was prepared by reacting aluminum chloride with 2-ethylhexoic acid. Limited data indicated that acetylene black, silica aerogel, and certain processed bentonites might be substituted for the aluminum octoate (ref. 16). The slurries were prepared at room temperature. The additives were thoroughly dispersed in the hydrocarbon, and the boron powder was then added in small portions. Intensive mixing was applied during the entire preparation procedure by use of a high-speed mixer that is illustrated in reference 15.

FLOW PROPERTIES OF BORON SLURRIES

The more satisfactory slurries were thixotropic at room temperature but tended to lose this characteristic when the temperature was raised to 80° C, as shown in figure 6. This behavior is discussed in references 15 and 17. A wide range of initial Brookfield apparent viscosities, from about 1500 to over 100,000 centipoises, was obtained by varying the concentrations of boron from 50 to 60 percent, of gelling additive from 0 to 0.4 percent, and of glyceryl sorbitan laurate from 0.5 to 4.0 percent (all proportions by weight). The variation of initial Brookfield apparent viscosity with additive concentration is shown in figure 7. The Brookfield viscosity increased so rapidly with boron concentration that it was impractical to use more than about 60 percent boron (ref. 15).
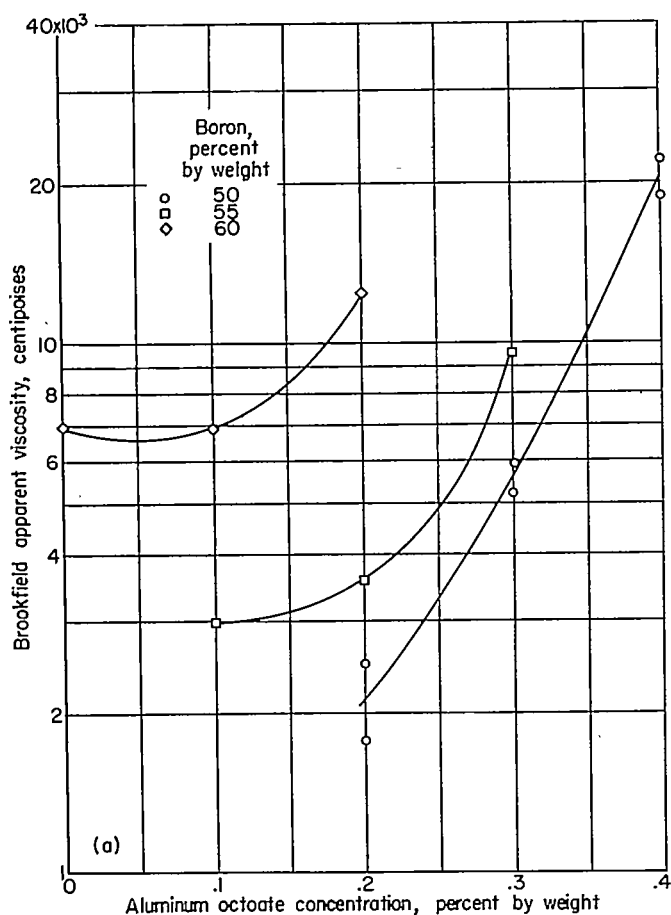
(a) Glyceryl sorbitan laurate concentration, 1.6 percent (ref. 15).
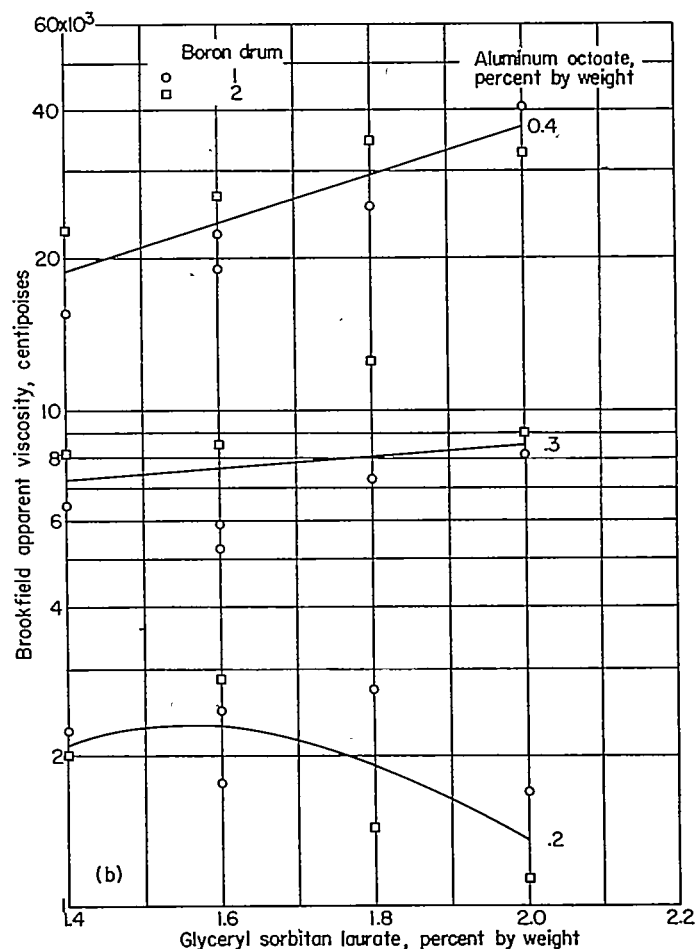
(b) Boron concentration, 50 percent (adapted from ref. 15).

FIGURE 7.—Effect of additive concentration on Brookfield apparent viscosities of boron slurries in JP-5 fuel.

STORAGE LIFE OF BORON SLURRIES

The gel structure of the boron slurries deteriorated during storage. After a time the boron settled to form a gummy cake that could not readily be redispersed, a condition representing the end of useful life of the slurry. This effect was sometimes accompanied by a decrease in Brookfield apparent viscosity, as shown in figure 8. This figure also indicates that at a given concentration of surface-active additive a higher concentration of aluminum octoate increased the useful life. However, the use of as much as 0.4 percent aluminum octoate was feasible only when the boron concentration did not exceed 50 percent. One factor that influenced the useful life was the acidity of the boron, as reflected by the pH of a water extract of the powder. Another factor was the moisture content, as measured by the percent weight loss of the powder at 105° C. When the pH was as high as 5.2 and the weight loss was as low as 0.4 percent, the initial viscosity was increased and useful life of laboratory samples extended beyond 6 months (ref. 15).

PREPARATION AND PROPERTIES OF MAGNESIUM SLURRIES

PREPARATION OF MAGNESIUM

Much of the experimental work on magnesium slurries was conducted with comparatively coarse, commercially available, 13- to 24-micron magnesium powder, prepared by atomization of the molten metal. This powder contained 94 percent or more elemental magnesium, the remainder being mainly oxide. The particles were predominantly spherical. Average particle diameters and particle size distributions were variously determined with sieves, microscope, Fisher Sub-Sieve Sizer, and Roller Analyzer (ref. 11).

After combustion studies indicated the desirability of using more finely divided magnesium, sources of such material were sought. Very limited quantities of 0.6- to 5-micron magnesium were obtained as byproducts of the commercial atomization process. The particles of this powder were irregularly shaped, but not appreciably flat or elongated. Attempts to grind magnesium gave flattened, elongated particles that yielded slurries with very poor flow properties.

The development of a process for making suitable, finely divided magnesium was undertaken because of the very limited commercial availability of such material. The result was a vapor process, based on the shock-chilling of magnesium vapor with jet-engine hydrocarbon fuel (refs. 18 and 19). Figure 9 is a diagram of a laboratory-size plant in which magnesium metal was vaporized at 2000° F in a 4-inch-diameter steel crucible heated with an induction coil. The helium atmosphere in the furnace chamber was kept at a pressure of 11 pounds per square inch gage, and a constant stream of helium carried the magnesium vapor through a heated orifice into a series of hydrocarbon sprays. Solidified magnesium that was deposited at the inlet to the condensing chamber tended to block the orifice, but the difficulty was alleviated by using a cylindrical chamber with thermal insulation on the inner face of the wall at the inlet. The best design permitted clog-free operation for about 6 hours. The dilute hydrocarbon suspension of magnesium was permitted to settle, and the sediment was centrifuged to produce a concentrate containing about 60 percent solids. The solids consisted of about 90 percent elemental magnesium. Electron micrographs indicated that the particles were irregularly shaped and that about 90 percent of them were 0.2 micron
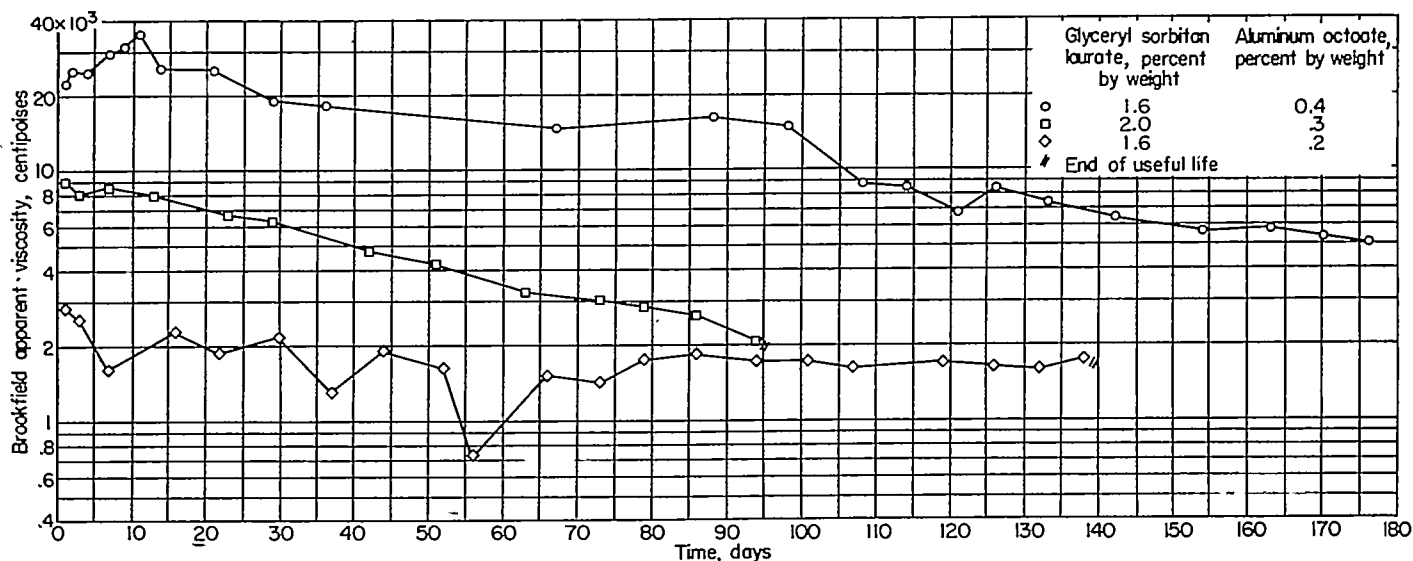

FIGURE 8.—Change of Brookfield apparent viscosity with age of boron slurries made with JP-5 fuel. Boron concentration, 50 percent (ref. 15).

or less in the longest dimension. Calculations based on minima in plots of yield value and Brookfield apparent viscosity against concentration of cetyl alcohol added to the slurry indicated the average equivalent spherical diameter to be 0.2 to 0.4 micron (ref. 20).

MAGNESIUM SLURRIES FLUIDIZED WITH SURFACE-ACTIVE ADDITIVES

Preparation.—The 60 percent solids concentrate of vapor-process magnesium was a pasty mass that had poor flow properties even when diluted to 50 percent solids with jet-engine hydrocarbon fuel. A 50 percent concentration of atomized magnesium with an average particle diameter less than about 2 microns also formed a paste. In order to obtain a smooth fluid suspension of either type of magnesium, it was necessary to stir in a surface-active additive and then run the suspension through a colloid mill.

A study of assorted surface-active additives showed that oil-dispersible compounds whose molecular structure included a hydroxyl group together with an ester, metal salt, or polyoxyethylene group were the most effective (refs. 9 and 21). Examples of such compounds are polyoxyethylene

sorbitol tetraoleate and glyceryl sorbitan laurate. It is believed that these combinations of functional groups were so effective because they provided a maximum of interaction between the molecules of additive and the oxide, hydrated oxide, sorbed moisture, or metal at the surfaces of the magnesium particles. In the case of oxide or hydrated surfaces, the interaction may have occurred through coordination and hydrogen bonding. In the case of metal surfaces, dipole interaction may have been involved (ref. 22).

Flow properties.—Slurries containing 50 percent of vapor-process magnesium or 1.5-micron atomized magnesium and no surface-active additive were thixotropic and behaved like pseudoplastic materials. When successively greater percentages of surface-active additive were incorporated, the flow behavior became more like that of a plastic material and the thixotropy disappeared (refs. 9 and 21). Figure 10 (also ref. 21) shows how the yield value, plastic viscosity, and Brookfield apparent viscosity of slurries of vapor-process magnesium decreased from their high values at 0 or 0.5 percent additive to their low values at 3 to 5 percent additive. Data in reference 9 indicate that slurries con-
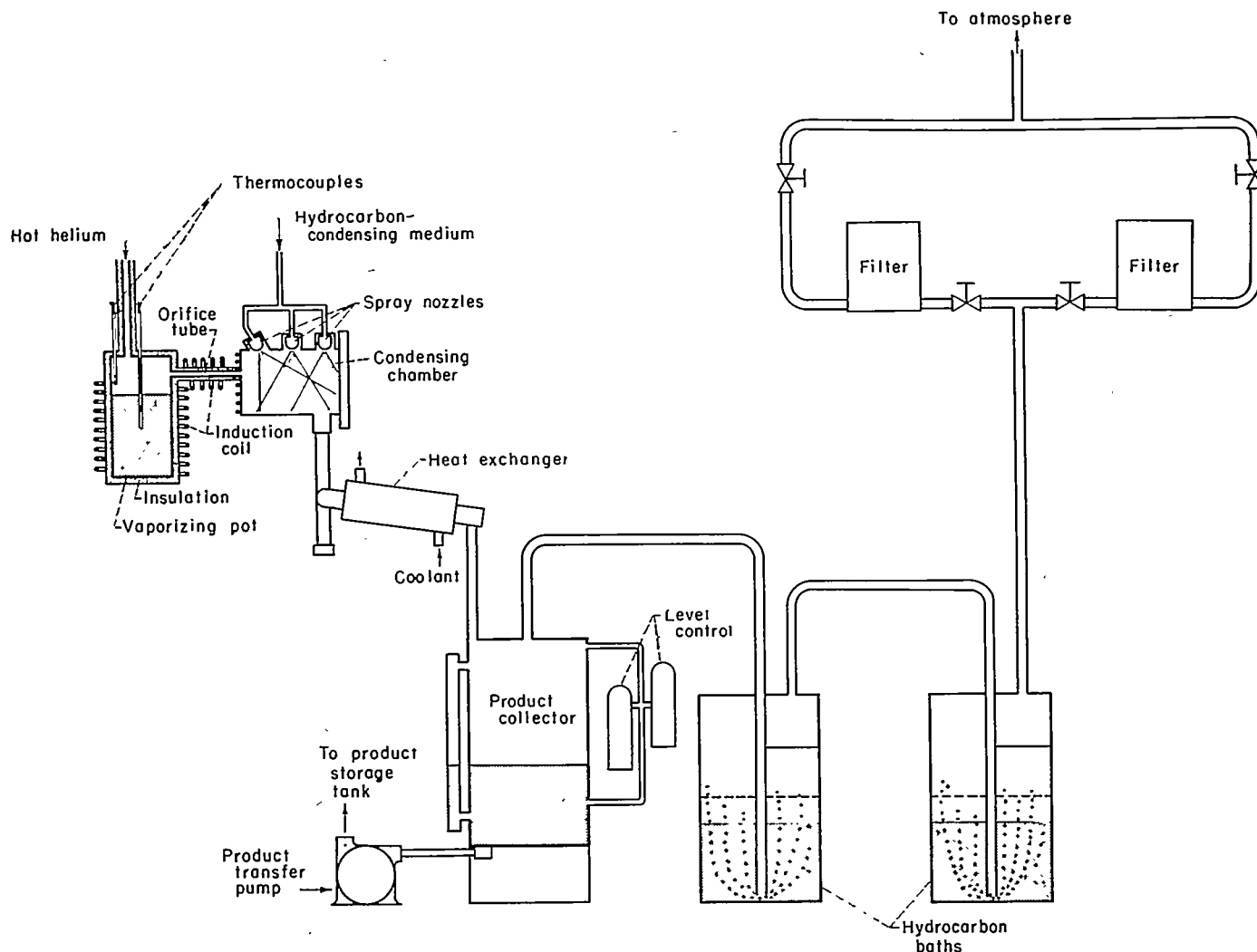

FIGURE 9.—Schematic diagram of magnesium vaporization unit (ref. 19).

taining 50 percent of 1.5-micron magnesium and only 1 percent surface-active additive were very fluid (plastic viscosity, 7 centipoises; yield value, 9 dynes/cm²; Brookfield apparent viscosity, 200 centipoises). Acceptable slurries containing 55 or 60 percent of 1.5-micron magnesium could readily be prepared. Data in reference 17 show that the viscosities and yield values were often decreased by two-thirds or more when the temperature was increased to 212° F. The effect of increasing the temperature was most pronounced for the thicker slurries. The slurries also tended to become more fluid during aging for about 1 month after they were first prepared. Good uniformity of successive mixes of slurry was readily obtained as long as the same batches of ingredients were used, but the effect of changing batches of magnesium was particularly noticeable (ref. 9).

Relation of flow properties to piping, spraying, and storage.—The flow properties of magnesium slurries were studied not only in viscometers, but also in a piping system consisting of nominal ⅜-inch- and 1-inch-diameter straight pipe and standard pipe fittings (ref. 23). The results indicated that published Newtonian pressure-loss coefficients can be satisfactorily used in the design of aircraft fuel systems for non-Newtonian slurries if account is taken of the flow properties of the slurries as determined with a suitable viscometer. The spray characteristics of slurries of vapor-process magnesium were relatively independent of plastic viscosity in the range of 220 to 510 centipoises and of yield value in the range of 150 to 810 dynes per square centimeter (ref. 24). This fact indicates that considerable leeway is permissible in the specification of the flow properties of these slurries insofar as they affect the injection of slurry into a jet-engine combustor.
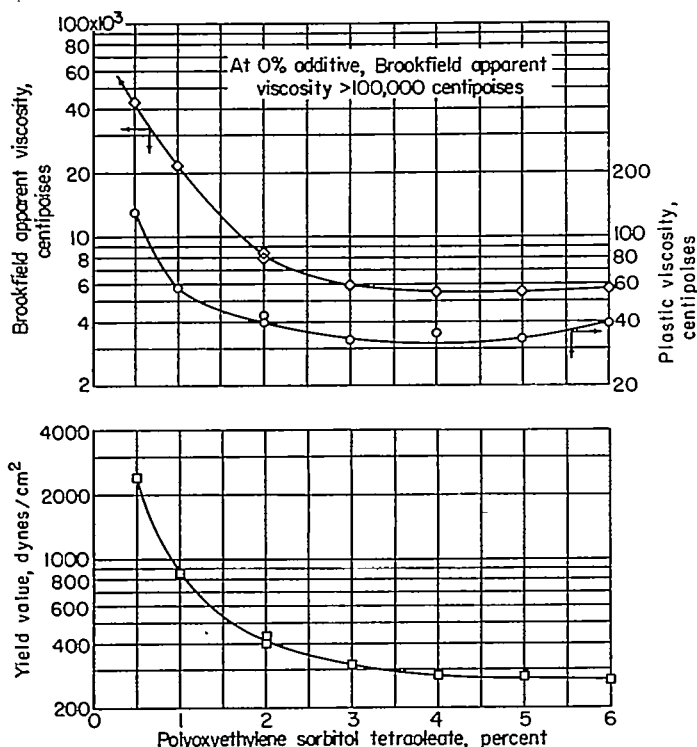

FIGURE 10.—Effect of concentration of additive on Brookfield apparent viscosity, plastic viscosity, and yield value of slurry containing 50 percent vapor-process magnesium. Additive, polyoxyethylene sorbitol tetraoleate (ref. 21).
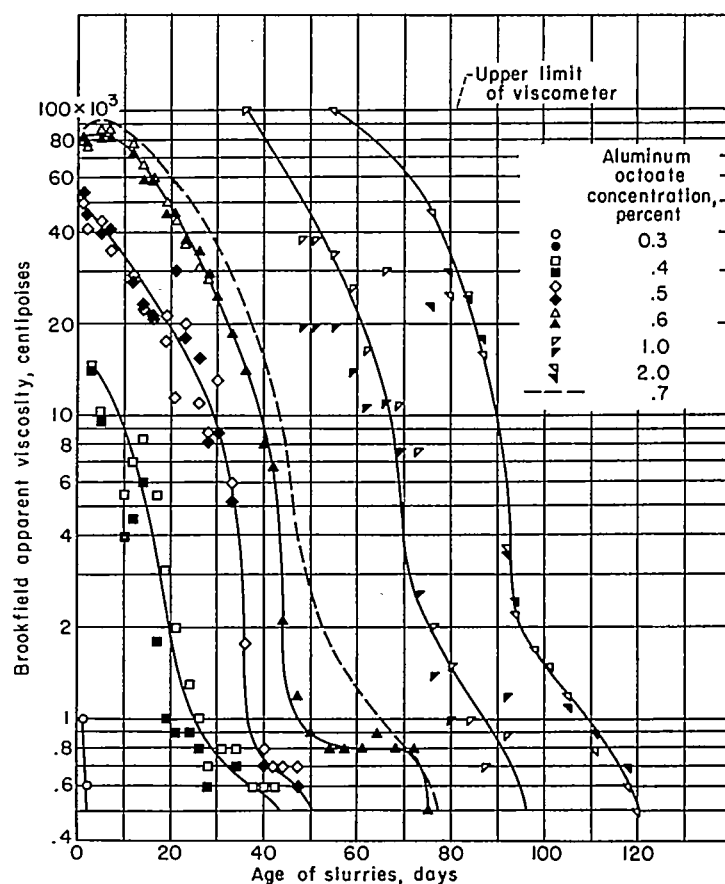

FIGURE 11.—Change of Brookfield apparent viscosity with age of slurries containing 50 percent 13-micron magnesium. Slurry gelled at approximately 110° F (ref. 26).

The settling and storage properties of slurries fluidized with surface-active additives were closely correlated with the flow properties (refs. 9 and 21). When the Brookfield apparent viscosity of slurries containing 50 percent 1.5-micron magnesium was 2500 to 4000 centipoises, only a small quantity of supernatant liquid formed during four weeks storage in 50-milliliter graduated cylinders. These slurries could readily be reconstituted by mixing. When these slurries were made progressively more fluid by the use of larger concentrations of surface-active additive, the quantity of supernatant liquid increased correspondingly until, at a Brookfield viscosity of about 200 centipoises, the magnesium settled into a hard cake that was difficult to redisperse in the abundant supernatant liquid. Even the most fluid slurries containing 50 percent vapor-process magnesium had a Brookfield viscosity of about 3500 centipoises, and they settled as little, and were as easily reconstituted, as the slurries of 1.5-micron magnesium of the same Brookfield viscosity.

MAGNESIUM SLURRIES THICKENED WITH GELLING AGENTS

Preparation.—As previously indicated, slurries of coarser, atomized magnesium were also examined. When the average particle size was about 4 microns or more it was necessary to thicken the hydrocarbon medium to retard settling. One method was to gel the hydrocarbon. The best gelling additive consisted of aluminum octoate, which was principally aluminum di(2-ethylhexoate) and was similar to the gelling additive used for boron slurries. Up to 1.2 percent of other grades of aluminum octoate in combination with other addi-

Airflow
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(a)

(b)

(c)
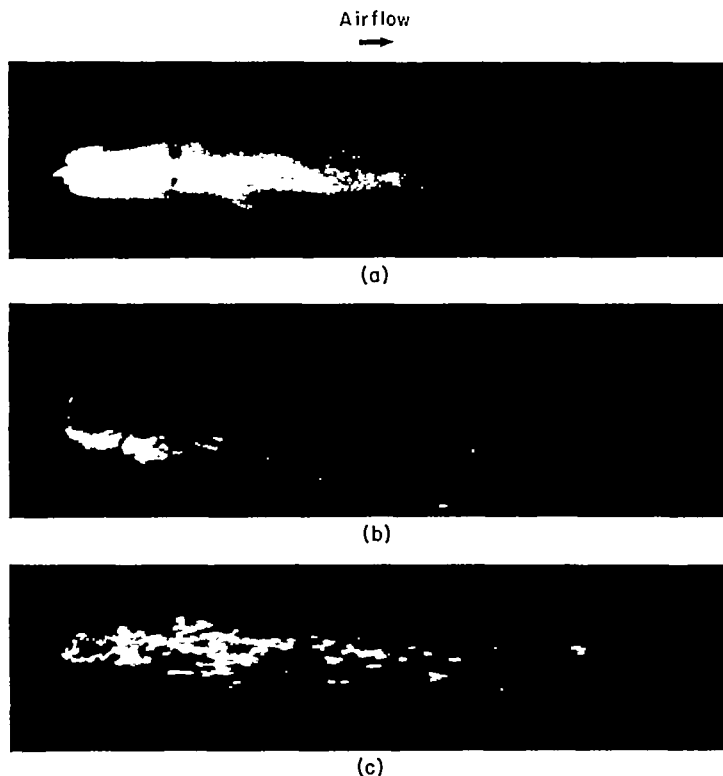
(a) JP-3 fuel; viscosity, 4 centipoises; no magnesium.
(b) 30-percent slurry of magnesium containing gelling additive; apparent viscosity, 300 to 400 centipoises.
(c) 30-percent slurry of magnesium containing gelling additive; apparent viscosity, 800 to 1600 centipoises.

FIGURE 12.—Photographs showing effect of gelling additive and magnesium on spray formation. Inlet air velocity, 400 feet per second; fuel jet velocity, approximately 26 feet per second; inlet air temperature, 80° F; inlet air density, 0.048 pound per cubic foot (ref. 27).

tives was used in earlier work (ref. 25). Various mixing procedures were used, but for batches weighing up to 200 pounds the combined ingredients were generally rolled in cans or drums on a roller enclosed in a box that could be heated. When 0.6 percent of aluminum octoate was used, a 100-pound batch of slurry containing 50 percent of 15-micron magnesium was gelled in about 4 hours at 90° F (ref. 26). Under closely controlled conditions, successive batches with very similar flow properties could be obtained from a single drum of magnesium; but, as in the case of the boron slurries, the gel structure was very sensitive to impurities and to small variations in the gelling additive or processing conditions.

Flow properties and storage behavior.—The flow properties of gelled magnesium slurries were similar to those of the gelled boron slurries. Although no studies were made over a range of rates of shear, the slurries were observed to be thixotropic. Also like the boron slurries, they deteriorated during storage, as shown by plots of Brookfield apparent viscosity against time in figure 11 (also ref. 26). This figure also indicates the effect of the concentration of gelling additive on the consistency of the slurry. The use of more than 0.7 percent gelling additive gave a very thick slurry initially and extended the length of time the gel structure was retained; but, even when 2.0 percent was used, the gel structure disappeared to such an extent in about 110 days that the slurry was no longer considered usable. However, these

measurements were made on small samples, two of which, containing 0.6 percent aluminum octoate, were taken from larger batches. It was later discovered that the remainders, which had been kept sealed in their original containers, were still of usable quality even after 5½ months of storage. It therefore appears that the storage life of gelled slurries may be subject to more variables than have been investigated and may be longer than is indicated in figure 11.

The relation of apparent viscosity to spray characteristics of gelled magnesium slurry is shown in high-speed photographs in figure 12 (taken from ref. 27). At an apparent viscosity of 800 to 1600 centipoises, the spray was coarser than at 300 to 400 centipoises, and both these sprays were much coarser than a spray of JP-3 fuel. This behavior appears to be in contrast with the previously mentioned lack of correlation between spray characteristics and flow properties of slurries of vapor-process magnesium. The difference may be at least partially attributable to the absence of gel structure in the latter slurries.
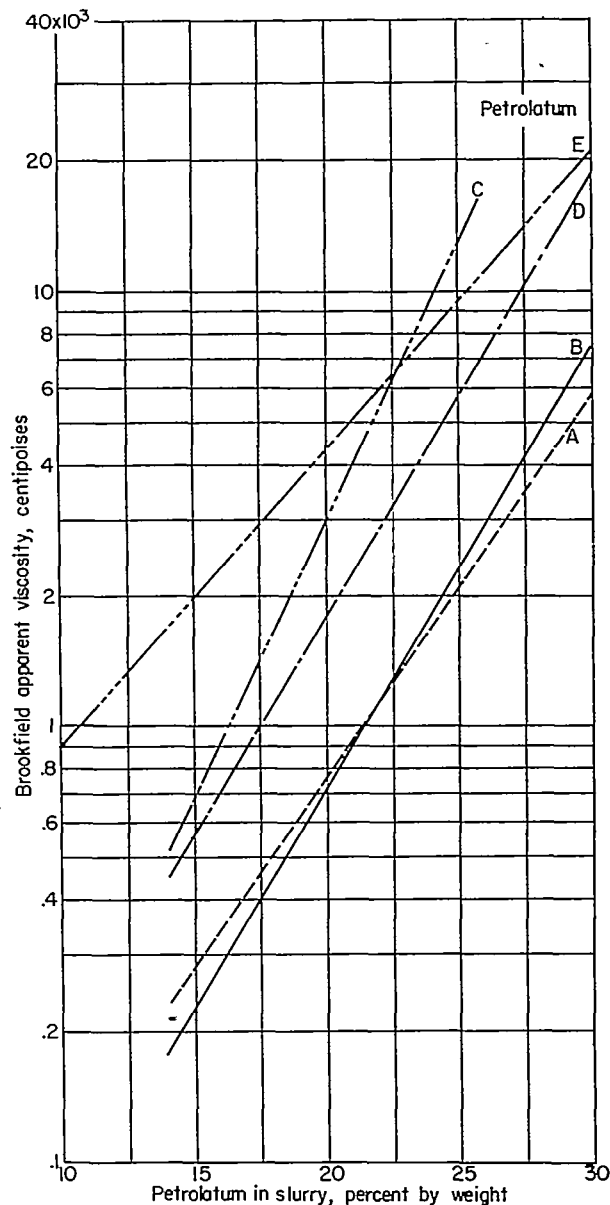

FIGURE 13.—Effect of concentration of various grades of petrolatum on Brookfield apparent viscosity of slurries containing JP-4 fuel and 50 percent 18-micron magnesium (ref. 11).

MAGNESIUM SLURRIES THICKENED WITH PETROLATUM

Preparation.—Another method used to stabilize slurries of coarser magnesium was to replace part of the jet fuel with petrolatum. When petrolatum with an ASTM melting point of 161° F and an ASTM penetration of 80 (petrolatum E in fig. 13) was used, the incorporation of 18 to 22 percent petrolatum in a slurry containing 50 percent 18-micron atomized magnesium gave the most satisfactory results (ref. 11). The magnesium concentration could also be increased to 65 percent by decreasing the petrolatum to 10 percent. The best preparative procedure was to mix the petrolatum with part of the jet fuel at 175° to 195° F, add the remainder of the jet fuel, add the magnesium powder and mix it in at 140° to 160° F, and then cool the mixture. Uniformity of successive mixes was readily obtained as long as the petrolatum came from the same batch, but the petrolatum concentration had to be adjusted for different batches of petrolatum.

Flow properties and storage behavior.—Limited data obtained for slurries containing 50 percent 18-micron magnesium and 18 to 26 percent petrolatum indicated that the slurries were plastic or slightly pseudoplastic mixtures (ref. 11). The Brookfield apparent viscosity was readily adjustable over a wide range (from about 160 centipoises, like thin paint, to about 16,000 centipoises, like apple butter) merely by selecting a suitable grade of petrolatum and varying the petrolatum concentration from 10 to 30 percent of the weight of slurry (fig. 13). Other factors controlling the viscosity were particle size and concentration of the magnesium (ref. 28). By choosing an appropriate concentration of petrolatum and keeping the average diameter of the spherical magnesium particles above about 7 microns, a satisfactory degree of fluidity could be maintained even when the magnesium concentration was raised to 60 or 65 percent.

The extent of settling that occurred during 28 days could be correlated quite closely with the Brookfield viscosity of the slurry. Some supernatant liquid always formed during this period, but when the Brookfield viscosity was about 4000 centipoises, the extent of settling was small and the slurry could readily be restored to its original condition by
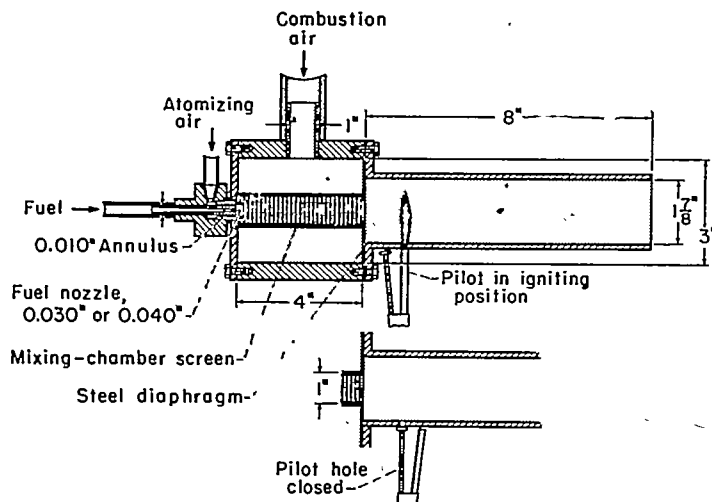
mixing. The extent of settling was minimized when the 4000-centipoise viscosity was attained by raising the magnesium concentration above 50 percent (ref. 11).

Photographs in reference 29 suggest that petrolatum-thickened slurry gave a more stringy spray than gelled slurry gave.

SUMMARY OF SLURRY PREPARATION AND PROPERTIES

Slurries can be made with high concentrations of finely divided boron or magnesium. Their shortcomings are (1) some nonuniformity of successive batches, particularly of boron slurries, (2) limited storage life, and (3) limited availability of the high purity, finely divided metals.

Exact slurry formulations cannot be recommended because of the difficulty of obtaining uniform batches of components and preparing uniform batches of product. However, when the components used are very similar to those that have been described, slurries comparable to the most satisfactory ones that were made can be prepared by using the following approximate formulations:

Boron slurry.—50 Percent boron (prepared by the magnesium reduction process), 0.2 to 0.4 percent aluminum octoate, 1.3 to 2.0 percent glyceryl sorbitan laurate, and 47.6 to 48.5 percent JP fuel.

Vapor-process magnesium slurry.—50 Percent vapor-process magnesium (in the form of a concentrate containing liquid hydrocarbon), 2.0 to 4.0 percent glyceryl sorbitan laurate, and 46 to 48 percent total hydrocarbon.

Gelled magnesium slurry.—50 Percent atomized magnesium (13 to 18 microns average particle diameter), 0.4 to 0.6 percent aluminum octoate, and 49.4 to 49.6 percent JP fuel.

Petrolatum-stabilized magnesium slurry.—50 Percent atomized magnesium (13 to 18 microns average particle diameter), 18 to 22 percent petrolatum, and 28 to 32 percent JP fuel.

COMBUSTION OF BORON SLURRIES
EXPLORATORY STUDIES

Exploratory studies were made of two combustion properties: blowout velocity (velocity of combustion air required to extinguish the flame), and combustion efficiency (percent conversion of each fuel component to oxidized products). Blowout velocities were measured in the burner shown in
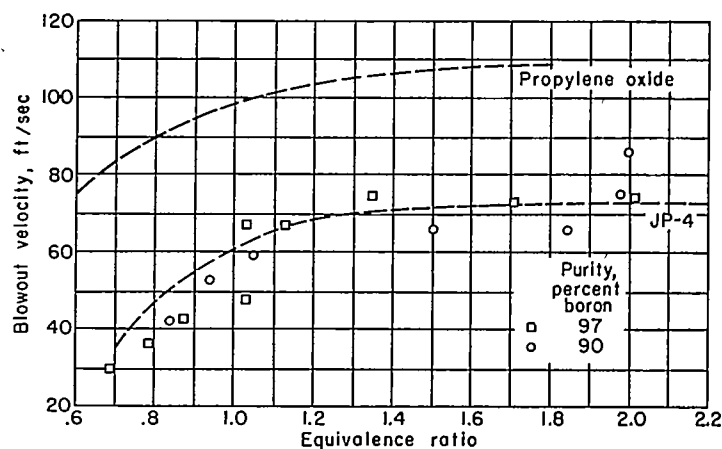

FIGURE 14.—Slurry burner for measurement of blowout velocities (ref. 30).

FIGURE 15.—Blowout velocities of propylene oxide, JP-4, and two 50 percent-boron slurries in 1⅜-inch-diameter burner. Slurries made with JP-4 fuel (ref. 2).
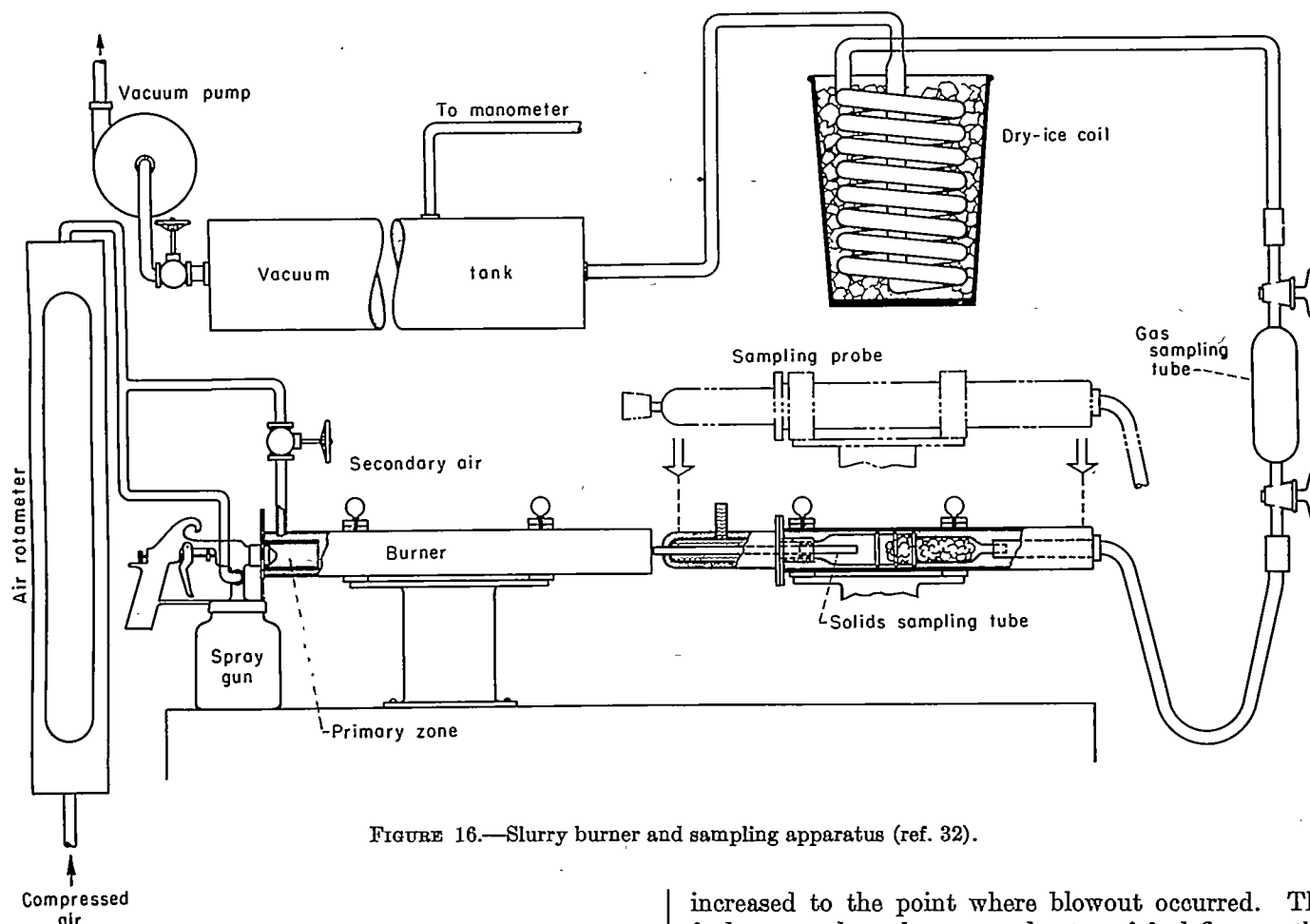
FIGURE 16.—Slurry burner and sampling apparatus (ref. 32).

figure 14 and in reference 30. The fuel was introduced through a small orifice and atomized with air. The atomized fuel entered a mixture preparation zone in which additional combustion air was added. The additional combustion air was introduced through a wall made of wire cloth that prevented the accumulation of solid particles on the wall of the preparation zone. The flame was seated in the recirculation zone established by the sudden expansion to the 1⅜-inch-inside-diameter tube. The mixture was ignited by a pilot flame that extended through a hole that was closed after ignition. The flow of combustion air was
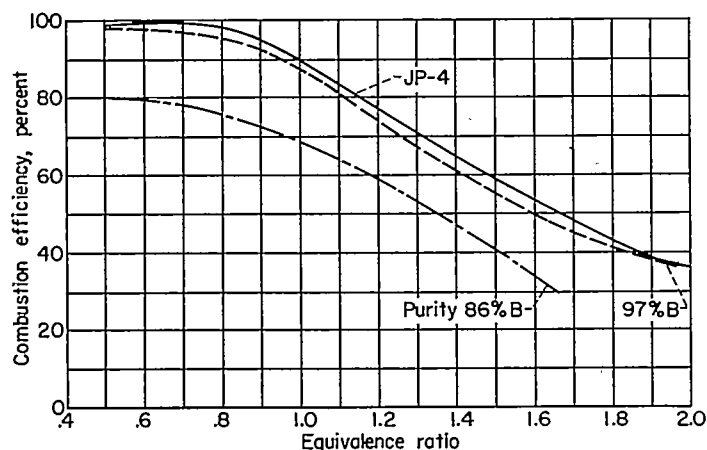

FIGURE 17.—Combustion efficiency of JP–4 and two 30-percent-boron slurries made with JP–4 fuel (ref. 2). Apparatus shown in figure 16.

increased to the point where blowout occurred. The test fuel was evaluated at several rates of fuel flow so that the blowout velocity could be determined for various fuel-air ratios.

Boron-slurry blowout velocities are reported in references 30 and 31. Figure 15 compares plots of blowout velocity against equivalence ratio (actual fuel-air ratio divided by stoichiometric fuel-air ratio) up to 2.0 for JP–4, propylene oxide, and two slurries containing 50 percent boron. Propylene oxide is a convenient comparison fuel, since it has roughly twice the laminar flame speed of hydrocarbons of the type found in JP–4. Although the two boron slurries differed somewhat in composition (90 percent boron purity, 1.0-micron average particle size, 1.6 percent surface-active agent, no gelling additive, against 97 percent, 0.7 micron, 1.3 percent, and 0.5 percent gelling additive), their blowout velocities were similar. As shown in figure 15, the boron slurries and the JP–4 fuel had substantially the same blowout velocities.

A similar exploration of combustion efficiency was conducted by analyzing combustion products. The apparatus shown in figure 16 was used. Boron slurry was injected with a modified paint spray gun, and the addition of secondary air formed a combustible mixture. The combustion products issuing from the combustor outlet passed through glass wool, which trapped the solid products, and the filtered gaseous products were collected in sampling tubes.

Figure 17 (based on data from ref. 32) shows combustion-efficiency data over the range of equivalence ratios of interest for JP–4 fuel and two slurries containing 30 percent boron but no additives. The combustion efficiency of the slurry
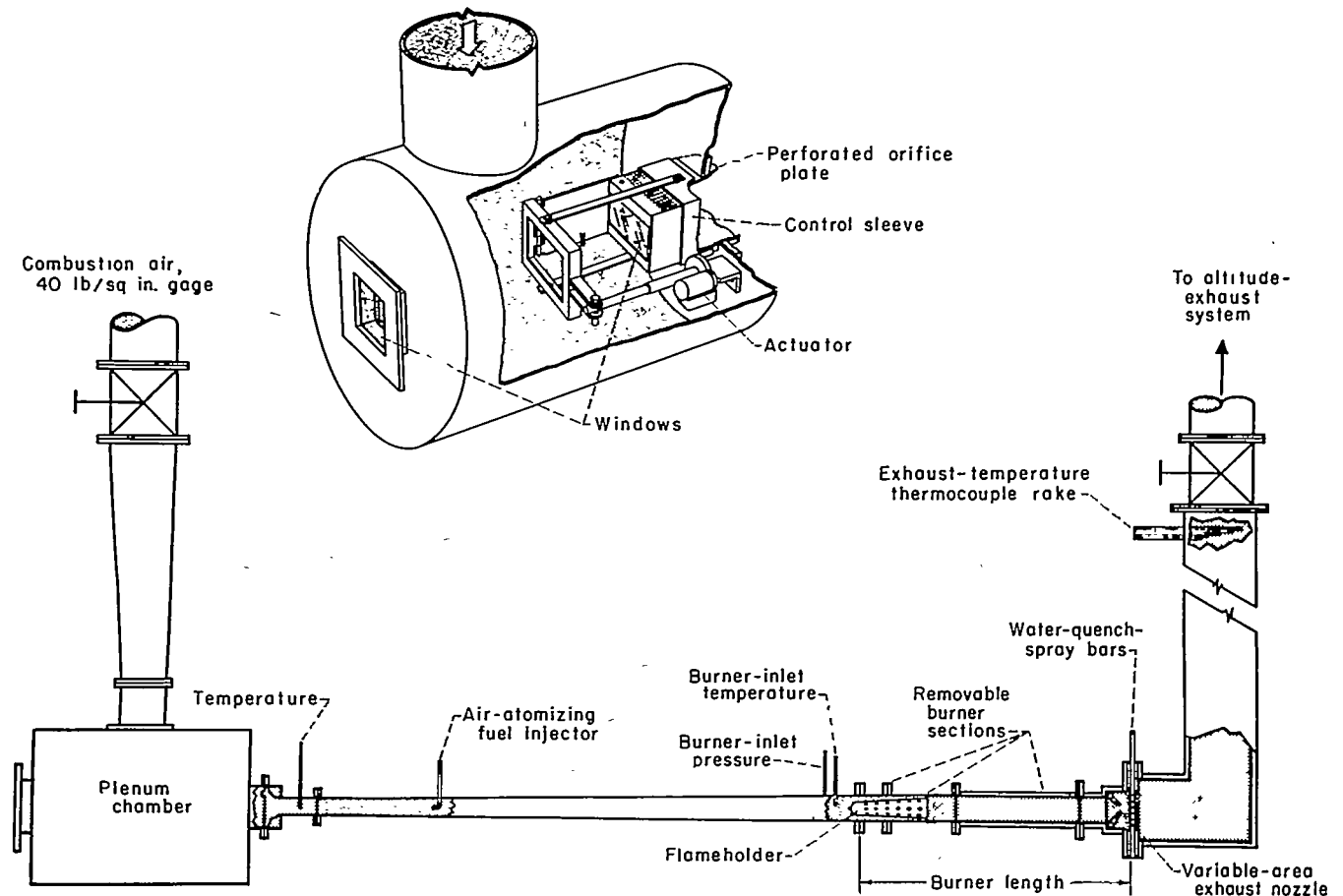
FIGURE 18.—Schematic diagram of 5-inch-diameter ramjet burner (ref. 33).

of 97-percent-pure boron was only a little lower than that of JP–4 over the entire range of equivalence ratios, while that of the slurry of 86-percent pure boron was 15 to 20 percentage points poorer.

LARGER-SCALE STUDIES

Since the exploratory data indicated that slurried boron could be made to burn almost as vigorously and efficiently as JP–4 fuel, it was next burned in the 5-inch-diameter simulated ramjet burner sketched in figure 18, taken from reference 33. Preheated air at pressures up to 40 pounds per square inch gage was supplied through a choked diffuser
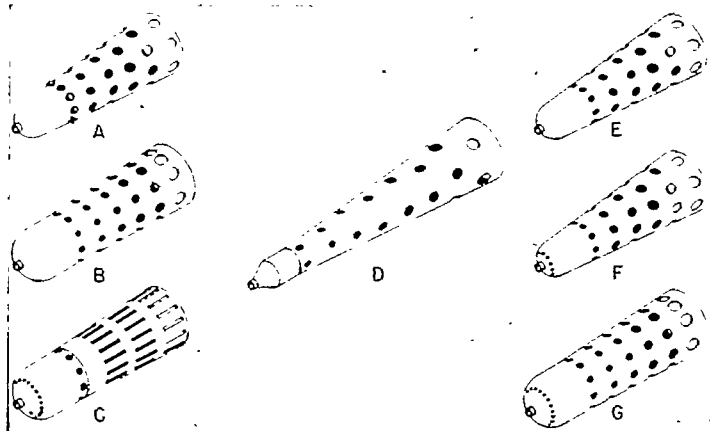
into the combustion zone. The combustion chamber length was varied between 40 and 52 inches; the combustor terminated in a variable-area exhaust nozzle. A water spray
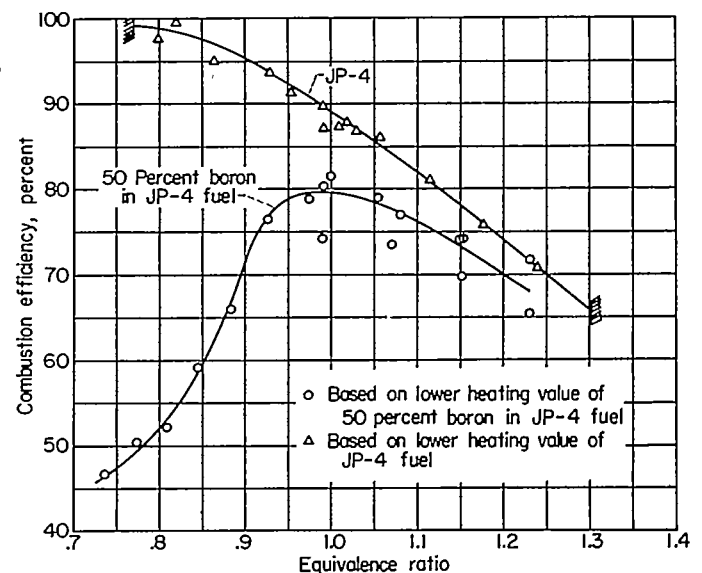

FIGURE 19.—Boron-slurry flameholders (ref. 2).

FIGURE 20.—Combustion efficiency of JP–4 fuel and boron slurry in 5-inch-diameter ramjet burner. Flameholder A shown in figure 19; burner length, 40 and 52 inches; inlet mixture temperature, 171° to 235° F; inlet pressure, 1692 to 2478 pounds per square foot absolute; inlet velocity, 123 to 181 feet per second; boron purity, 87 to 91 percent (ref. 33).

quenched the exhaust gases immediately downstream of the exhaust nozzle. The temperature of the quenched gases was measured by thermocouples downstream. Combustion efficiency was calculated from a heat balance across the system.

The can-type flameholders used in this program are shown in figure 19. The V-gutter types of flameholders originally used were discontinued because of poor combustion performance. The modifications in the can-type flameholders included the usual combustor design variables, such as blocked area, airflow distribution, and combustion-chamber length. Flameholder A in figure 19 gave the best performance. It was felt that the fuel-collecting scoops or shrouds around the first band of holes encouraged the recirculation of the boron into the upstream region of this flameholder.

The data from the 5-inch-diameter burner are summarized in figure 20 (taken from ref. 33), in which combustion efficiency is plotted against equivalence ratio. Gelled boron slurries consisting of 50 percent boron powder, 1.6 percent glyceryl sorbitan laurate, 0.4 percent aluminum octoate, and 48 percent JP-4 were evaluated and compared with JP-4 fuel alone. The boron powder was 87 to 91 percent pure, since the 97-percent-pure boron, which gave the more favorable results in the 1⅜-inch burner, was not available in sufficient quantity. The highest combustion efficiency obtained from the slurries was approximately 80 percent, considerably lower than that of JP-4, particularly at low equivalence ratios. The performance was about the same as that obtained with the corresponding grade of boron in the 1⅜-inch burner (fig. 17).

The principal observations that were made as a result of these and other data in the program were as follows: Heat outputs higher than the theoretical for JP-4 fuel were attained with boron fuels at high fuel-air ratios. A very high flame temperature was necessary for efficient combustion, as indicated by the high efficiencies only at near-stoichiometric fuel-air ratio. Scoops to encourage the recirculation of boron in the primary zone increased the efficiency. Combustion-chamber-length variations between 40 and 52 inches had little influence on combustion efficiency. Small variations in fuel composition had little influence on combustion performance.

Since the primary application for boron slurries would be in long-range, ramjet-powered vehicles where it is desirable to operate at low temperature ratios and hence low over-all fuel-air ratios, it seemed that some type of flow stratifica-
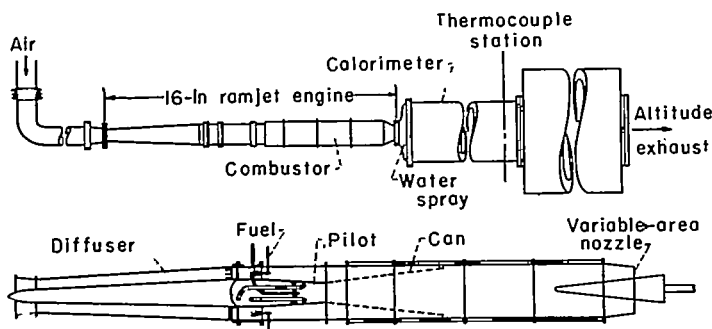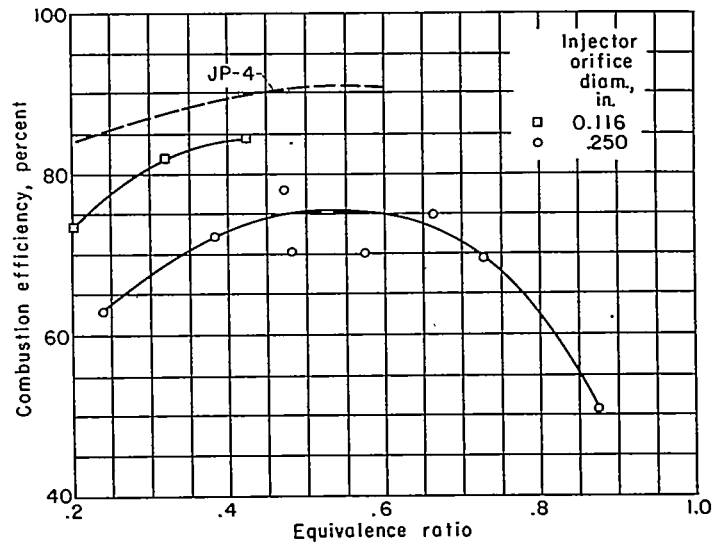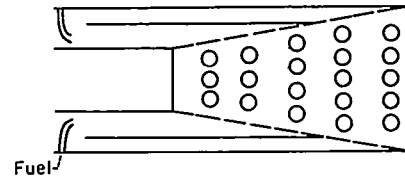

FIGURE 22.—Combustion efficiency of JP-4 fuel and boron slurry in 16-inch-diameter ramjet combustor. Pressure, 1 atmosphere; velocity, 260 feet per second; temperature, 560° F (ref. 2).

tion to produce a rich fuel mixture in the combustion chamber was necessary to achieve high combustion efficiencies.

The 16-inch-diameter ramjet engine shown in figure 21 (ref. 2) was used to facilitate construction of combustors with a bypass or stratified combustion zone. The fuel was fed from air-atomizing injectors. The fuel was kept inside a cylindrical sleeve that ensured fuel-air ratios near stoichiometric in the primary zone of the combustor even at over-all fuel-air ratios that were lean. The remainder of the air was bypassed around the fuel-control sleeve and was mixed downstream of the primary zone. The details of the 16-inch-diameter engine resemble actual design layouts used in ramjet engines. Combustion efficiency was measured by heat balance across the system.

One set of data that was obtained in this equipment is shown in figure 22 (data from ref. 34). Combustion efficiency is plotted against equivalence ratio for two injector systems. The maximum combustion efficiency with the injectors with 0.250-inch fuel orifices was 75 percent at an equivalence ratio of 0.5. The use of smaller injectors

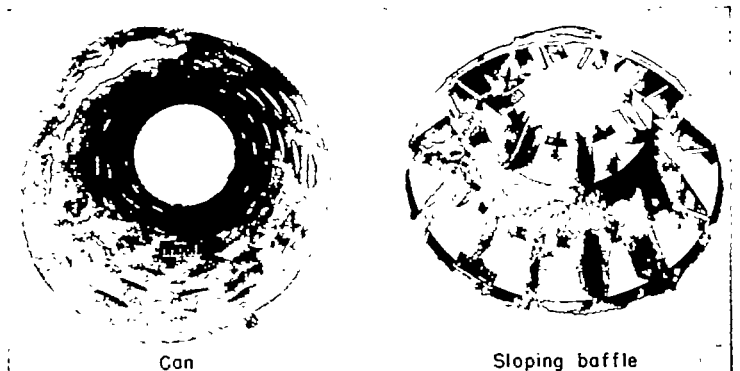FIGURE 21.—16-Inch-diameter ramjet engine used for boron fuels (ref. 2).

FIGURE 23.—Combustors after boron slurry was burned in them (ref. 2).

(0.116-in. orifice) increased the combustion efficiency to about 85 percent at an equivalence ratio of 0.4. The combustion efficiency for the boron slurries was consistently lower than that of JP-4 fuel evaluated at the same conditions.

Other problems found in the 16-inch-diameter engine tests with boron slurries are illustrated in figure 23. The high local temperature resulting from combustion at locally rich fuel-air ratios destroyed the can combustor. On the other hand, when the combustor parts were cooler, as with the sloping baffle system, heavy, clinker-like deposits formed on the surface.

Boron oxide virtually solidifies at temperatures of about 1000° F; reference 35 cites a viscosity of 1,000,000 centipoises for boron oxide at this temperature.

Thus, a satisfactory combustor design for boron slurry fuels has not been achieved. The high temperature required for high combustion efficiency destroyed engine parts, while lower combustor temperatures resulted in deposition problems and low combustion efficiencies. It may be that improved fuel atomization and the use of a fuel-controlling sleeve would produce peak combustion efficiencies at the relatively lean fuel-air ratios desired for application to the long-range ramjet missile.

COMBUSTION OF MAGNESIUM SLURRIES

EXPLORATORY STUDIES

Blowout velocities of various magnesium slurries containing petrolatum, gelling additive, or no additive at all have been measured with the burners shown in figures 14 and 16 (refs. 30, 31, and 36). Invariably, as the average particle diameter decreased, the blowout velocity progressively increased until, with 1.5-micron or vapor-process magnesium, the flame could not be blown out at velocities within the limits of the apparatus even at equivalence ratios less than
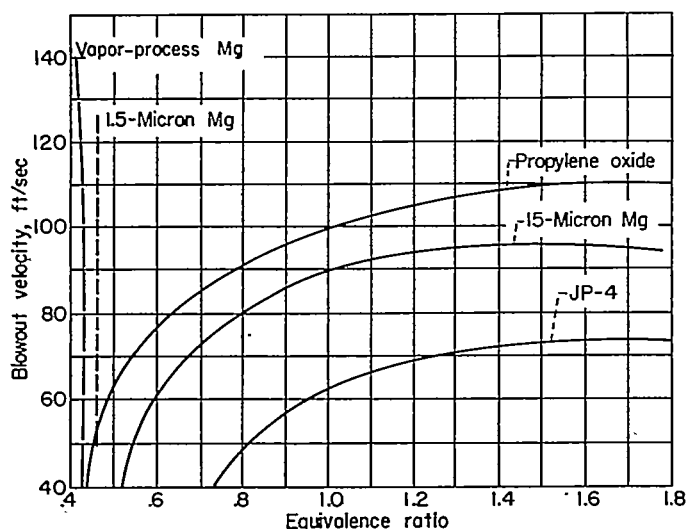

FIGURE 24.—Blowout velocities of propylene oxide, JP-4, and slurries containing 50 percent magnesium of different average particle sizes. Data obtained with 1⅞-inch-diameter burner shown in figure 14. (Adapted from ref. 30.)
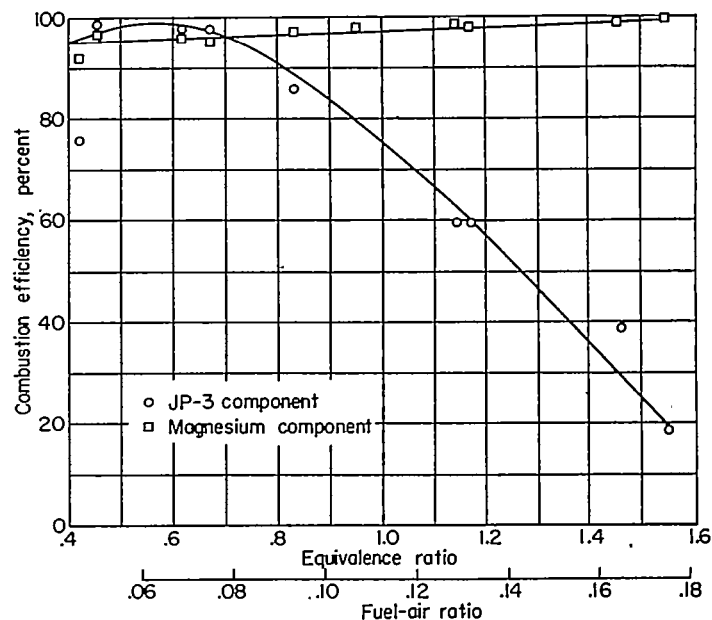

FIGURE 25.—Effect of equivalence ratio and fuel-air ratio on combustion efficiency of magnesium and hydrocarbon in slurry consisting of 50 percent 24-micron magnesium, JP-3, and 0.8 percent gelling additive (ref. 32).

required to support a JP-4 flame. It is for this reason that much effort was spent in obtaining very finely divided magnesium of suitable particle shape. Figure 24 shows some examples of the effect of particle size on the blowout velocity of slurries containing 50 percent magnesium. Comparison with figure 15 shows that, unlike slurries of boron, slurries of even the relatively coarse 15-micron magnesium had blowout velocities greater than that of JP-4.

The combustion efficiency of magnesium slurries was greater than 90 percent over a wide range of equivalence ratios even when the magnesium was as coarse as 24 microns in diameter (refs. 32 and 36), and it was even higher when the average particle size was smaller. At equivalence ratios above about 0.7, the combustion of the magnesium was nearly complete even though the combustion efficiency of the hydrocarbon medium began to decrease. Since there was insufficient oxygen to completely burn both the magnesium and the hydrocarbon, the decreasing combustion efficiency of the hydrocarbon indicates that the magnesium was preferentially reacting with the oxygen. This effect can be observed in figure 25.

Basic combustion data for magnesium have been obtained by experimentally observing the burning times for magnesium ribbons (ref. 37) in various mixtures of oxygen in argon, nitrogen, and helium. Some of the experiments were conducted with various percentages of water in argon-oxygen mixtures. The burning times of magnesium ribbons of 0.015- by 0.31-centimeter cross section decreased by a factor of approximately 10 with increasing oxygen concentration over the range 17 to 100 percent by volume. The times were slightly longer with argon mixtures than with nitrogen mixtures and were much shortened with helium mixtures.

Increasing the moisture content shortened the burning time somewhat.

Photographs showed that the magnesium ribbon vaporized as it burned. Consequently, burning times were calculated from a heat- and mass-transfer mechanism quite analogous to that used for calculating the burning times of liquid fuel drops. An important difference was that the concept of an infinitesimally thin flame front used for liquid-fuel drops was not used. Instead, the magnesium ribbon was assumed to burn in a high-temperature reaction zone of finite thickness. Excellent qualitative agreement between experiment and calculation was achieved; also, actual numerical values agreed within a factor of 2 to 3.

It therefore appears that magnesium slurries burn much more rapidly and over a wider range of equivalence ratios than boron slurries because the difference between flame temperature and boiling point of magnesium is much larger

FIGURE 27.—Net thrust obtained from JP-3 fuel and magnesium slurries in 6-inch-diameter afterburner-type combustor. Slurries contained rather coarse magnesium and no additive (ref. 2).
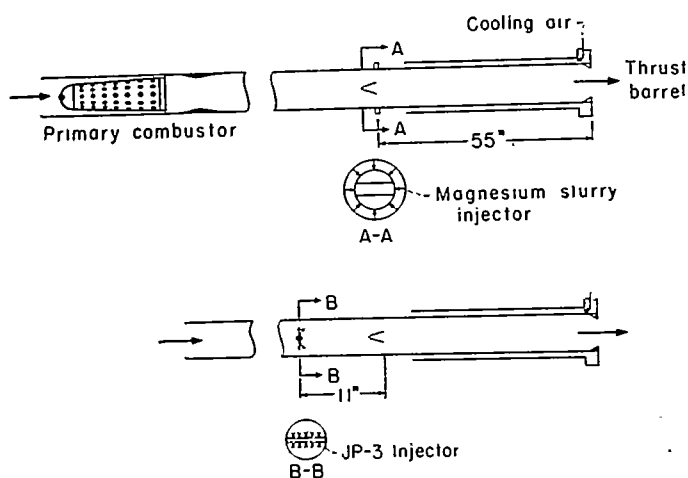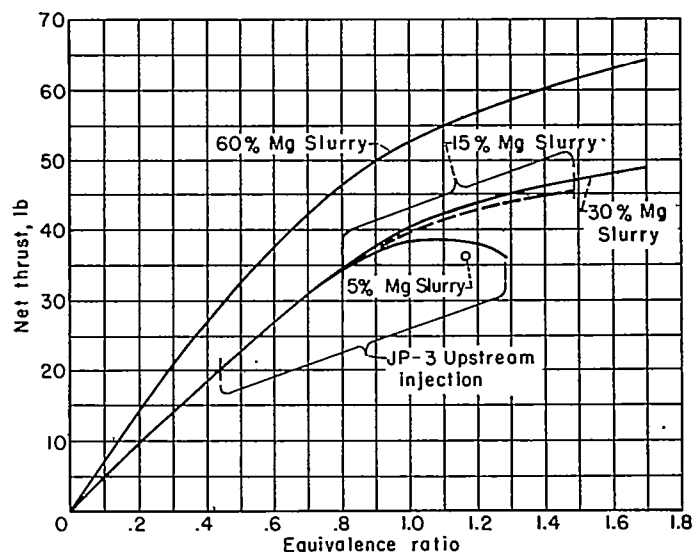

FIGURE 26.—Afterburner-type combustor, 6 inches in diameter, for burning magnesium slurry and JP-3 fuel (ref. 2). Flameholder blocked area, 31 percent.

than that of boron. Thus, a larger temperature gradient for heat and mass transfer exists for magnesium than for boron during combustion.

COMBUSTION IN AFTERBURNERS

A 6-inch-diameter afterburner-type combustor was operated on magnesium slurry (ref. 27). The small size of this afterburner was set by the limited quantities of magnesium-slurry fuels available. The apparatus is shown in figure 26. A single turbojet combustor provided gases of the same temperature and composition that would enter a full-scale afterburner. Jet thrust was measured in the thrust barrel. Magnesium slurry was injected from eight radial stations located exactly at the downstream edge of a single V-gutter than spanned the 6-inch test section (see section A-A, fig. 26), because the V-gutter was burned out when the slurry was injected upstream of the gutter. JP-3 fuel, which was used for comparison, was injected from a spray bar (section B-B) located 11 inches upstream of the V-gutter. When JP-3 fuel was injected at the plane of the V-gutter, it would not burn satisfactorily.

Typical data from the apparatus of figure 26 are shown in figure 27. The slurries were made from rather coarse magnesium and contained no thickening additive. Net thrust of the 6-inch afterburner is plotted against equivalence ratio for the various fuels shown. High-concentration slurries burned over much wider ranges than did JP-3 fuel. Furthermore, increasing the concentration of magnesium in the slurry increased the thrust, as predicted by thermodynamic calculations.

If water injection in the turbojet engine were combined with afterburning, the engine should get the combined thrust augmentation of both systems. However, the experience is that water injection, particularly at high water-flow rates, adversely affects the combustion efficiency in an afterburner burning conventional jet fuels. The effectiveness of the combined system is reduced. High water-flow rates may even extinguish the afterburner flame. Because of this problem, the effects of water on the combustion of JP-3 and on the combustion of magnesium slurry were determined in the rig shown in figure 26. Typical data appear in figure 28 (also ref. 38).
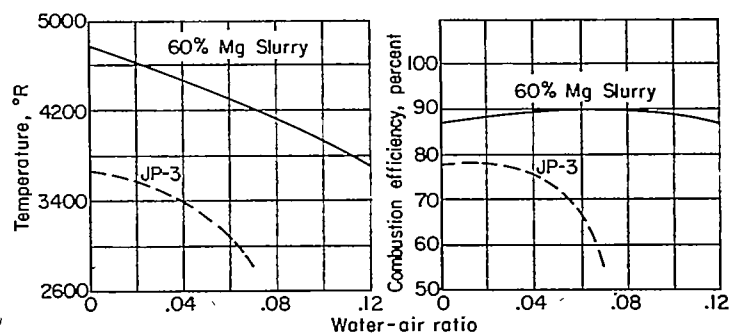

FIGURE 28.—Performance obtained from JP-3 fuel and magnesium slurry in 6-inch-diameter afterburner-type combustor with water injection. Stoichiometric combustion; slurries contained rather coarse magnesium and no additives (ref. 2).

At high water-air ratios, the temperature at the end of the afterburner decreased with both JP-3 fuel and with the 60 percent magnesium slurry because of the high dilution with water. Further analysis of the data, however, shows that the combustion efficiency of the JP-3 fuel was much reduced at water-air ratios above 0.04, while the combustion efficiency of 60 percent magnesium slurry was essentially unaffected. Unlike hydrocarbons, magnesium slurry burned quite vigorously and at high combustion efficiencies in the small afterburner even at high water-flow rates.

Thrust-augmentation data are summarized in figure 29. Curve A shows thrust augmentation obtained experimentally in a full-scale turbojet engine with coolant (75 percent water and 25 percent alcohol, by weight) injection, but without an afterburner. About 27-percent augmentation was achieved at a liquid ratio of about 7; that is, seven times the normal fuel-flow rate of the engine with no thrust augmentation. About 52-percent thrust augmentation was obtained experimentally by afterburning without coolant injection, as indicated by the circle; a liquid ratio of 4 was required. When experimental runs were made using coolant injection combined with stoichiometric combustion of JP-3 fuel in an afterburner, curve B was obtained. The maximum augmentation achieved in these runs was about 70 percent; higher coolant-flow rates caused unstable operation (ref. 2).

If slurry fuel containing 60 percent magnesium were burned stoichiometrically in a full-scale afterburner, and no coolant injection were used, the estimated augmentation would be as shown by the square in figure 29. This estimate is based on the combustion efficiency of the slurry in the small-scale afterburner of figure 28. When the latter combustion efficiency is combined with coolant injection, the estimated augmentation is that indicated by curve C, which predicts 100-percent thrust increase at a liquid ratio of 13.5. This prediction assumes that coolant injection would give the same combustion efficiency as water injection (indicated in ref. 39).

One very short-duration run with 60 percent magnesium slurry has been made. Combustion was stoichiometric and no water injection was used. The experimental thrust augmentation, indicated in figure 29 by the diamond, agreed quite closely with the predicted performance, indicated by the square.

COMBUSTION IN RAMJET MOUNTED IN CONNECTED-PIPE FACILITY

Magnesium slurry was also considered as a fuel for ramjet engines. Its high chemical reactivity, high air specific-impulse potential, and high fuel-volume specific impulse indicated magnesium slurry should be suitable for short-range ramjet vehicles. A joint program with the NACA Langley laboratory was undertaken to develop a ground-launched, rocket-boosted vehicle. It was expected that extension of the magnesium-slurry fuel research to a flight application would uncover difficulties that might otherwise have been missed. The Langley laboratory had an ethylene-fueled, aerodynamic test vehicle (ref. 40) that could be adapted to burn magnesium slurry. Ethylene had originally been selected, despite its low density, because its high flame speed made it suitable for use in a short combustor.

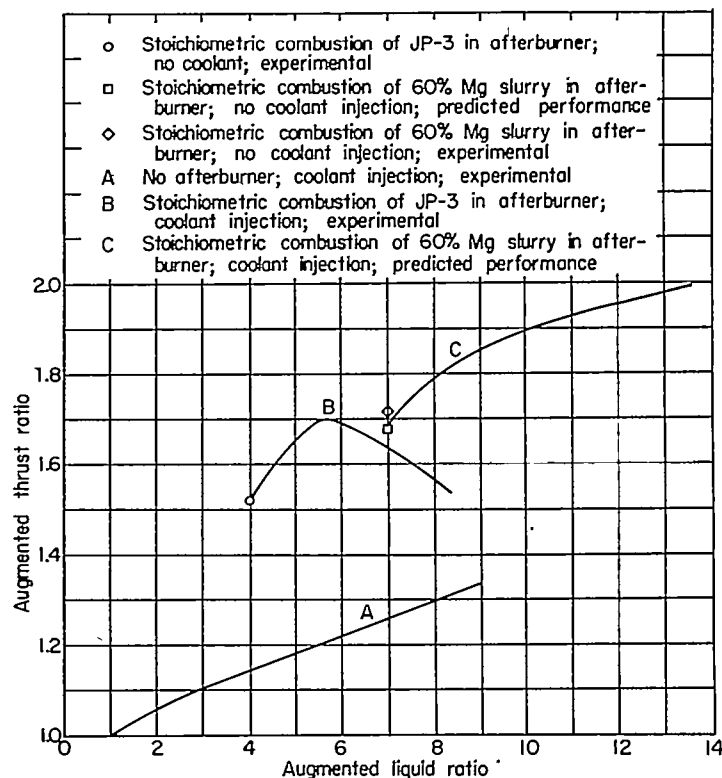The engine used in connected-pipe tests for developing a

FIGURE 29.—Static sea-level thrust augmentation of turbojet engine combining afterburning with water or coolant injection. Coolant, 75 percent water plus 25 percent alcohol. (Adapted from ref. 38 with data added from ref. 2.)

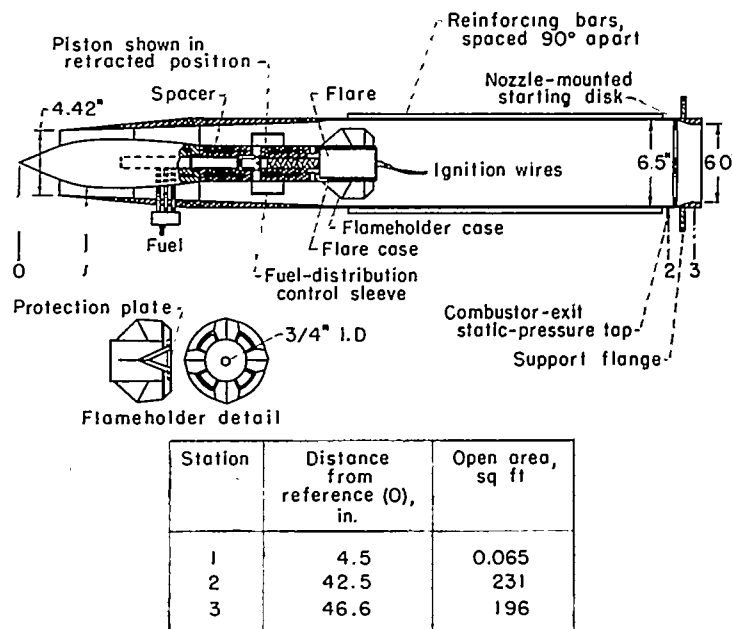| Station	Distance from reference (0), in.	Open area, sq ft
1	4.5	0.065
2	42.5	231
3	46.6	196

FIGURE 30.—Ramjet engine for development of combustor for flight tests (ref. 42).

slurry fuel is shown in figure 30. Its design was the result of an extensive study for fuel-injection devices, flameholders, starting disks, and other features that are discussed in references 41 and 42. Slurry fuel was introduced through a spring-loaded, variable-port-area injector with four longitudinal slots spaced 90° apart. Ignition was achieved with an electrically ignited flare, as shown in the figure. The

combustion chamber was 19 inches long, and the gutter-funnel-type flameholder blocked 46 percent of the combustor cross-sectional area. Starting was facilitated by mounting an aluminum disk upstream of the exit nozzle to block part of the nozzle area (ref. 42). After ignition occurred, the disk mountings burned away rapidly and permitted the disk to be expelled through the nozzle.

This engine was connected to a pipe facility that fed air at 30 to 60 pounds per square inch absolute and 63° to 367° F into the inlet. The combustion products were discharged into a barrel-type thrust target mounted in a plenum chamber and were eventually discharged to the atmosphere.

The performance of magnesium-slurry fuel consisting of 50 percent of 93-percent-pure atomized magnesium of 1.5-micron average particle diameter, 50 percent JP–4, and no additives has been compared with the performance of ethylene in a similar engine (ref. 42). Fuel-weight specific impulse is plotted against air specific impulse for slurry and ethylene fuels in figure 31 (a). The ideal performance data for the slurry and octene-1 fuels were obtained from reference 7, and for ethylene from reference 43. Over the range of air specific impulse obtained with ethylene, the fuel-weight specific impulse of ethylene was greater than that of the slurry. At an air specific impulse of 159 seconds, which was the maximum obtained with ethylene, the fuel-weight specific impulses of the ethylene and the slurry were 2350 and 1950 seconds, respectively. The slurry fuel permitted operation up to an air specific impulse of 187 seconds at a maximum combustor efficiency of about 82 percent (ref. 42).

Fuel-volume specific impulse, an index of fuel economy on a volume basis obtained by multiplying air specific impulse by fuel density and dividing by fuel-air ratio, is presented in figure 31 (b) as a function of air specific impulse. A density of 18.3 pounds per cubic foot was used for the ethylene volume impulse computation. This density was obtained when the flight fuel tank was pressurized to 1200 pounds per square inch. The fuel-volume specific impulse of the slurry was 2.6 and 2.9 times that of ethylene at air specific impulses of 140 and 159 seconds, respectively. At air specific impulses of 150 to 170, the experimental fuel-volume impulse of the slurry was about 10 percent lower than the ideal volume impulse for octene-1.
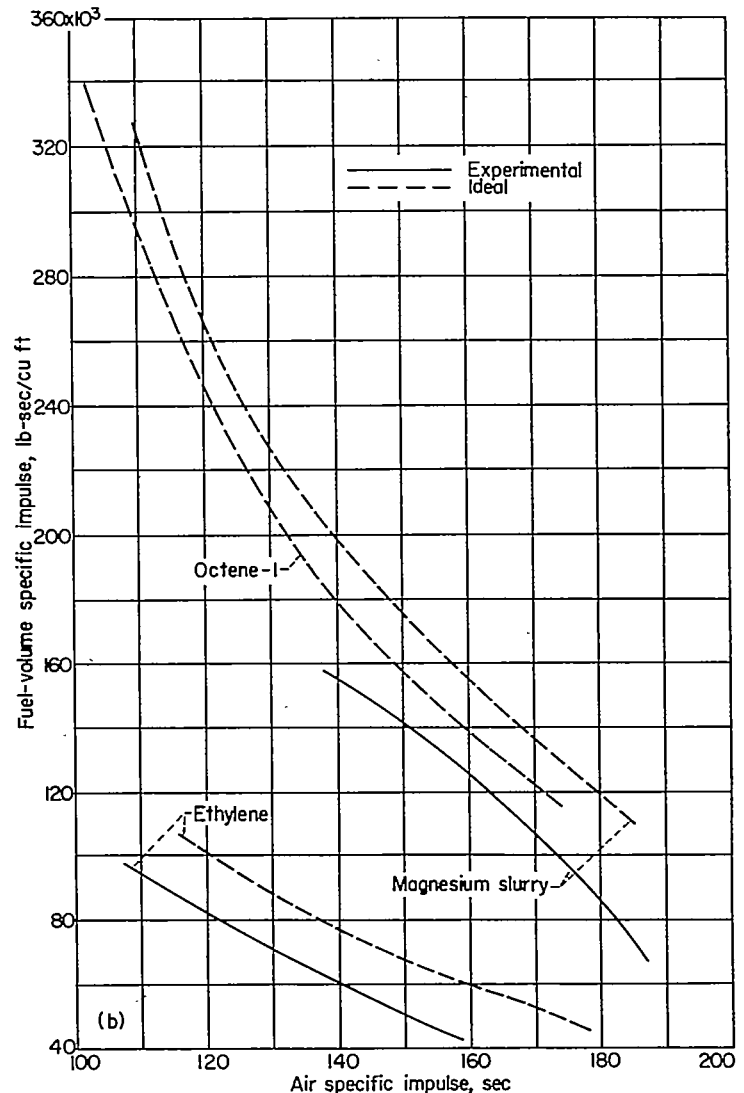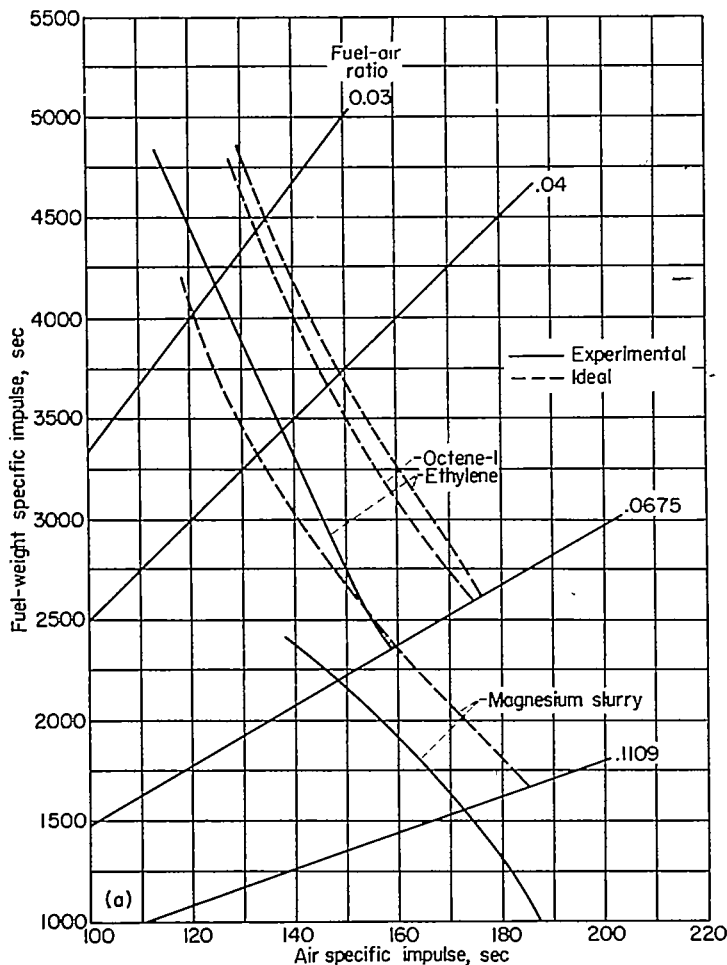
(a) Fuel-weight specific impulse as function of air specific impulse.

(b) Fuel-volume specific impulse as function of air specific impulse.

FIGURE 31.—Comparison of impulse data for three fuels. Slurry, 50 percent 1.5-micron magnesium, 50 percent JP–4, and no additives; combustor-inlet stagnation temperature, 350° F; sonic discharge of exhaust products (ref. 42).

The fuel-volume specific impulse is a significant parameter when applied to vehicles that have a small ratio of fuel weight to gross vehicle weight. For example, the Langley flight vehicle had an ethylene fuel- to gross-weight ratio of 0.1. Hence, a large increase in volume specific fuel consumption can make possible a correspondingly large increase in fuel load with only a small increase in vehicle gross weight. It was therefore concluded that the replacement of ethylene by magnesium slurry in the NACA Langley flight-test vehicle should result in improved performance.

PERFORMANCE OF MAGNESIUM SLURRY IN FLIGHT TESTS

Three flight tests of small rocket-launched ramjet test vehicles fueled with magnesium slurry were conducted at the Langley Pilotless Aircraft Research Station. The engines of these vehicles were similar to the 6.5-inch ramjet combustor that has been discussed. The first and third tests, conducted with single-engine vehicles, were considered successful, since good flame stability and reasonably good over-all performance of fuel and mechanical components were achieved (refs. 44 and 45). The second test, using a twin-engine vehicle, was less satisfactory because an abrupt decrease in thrust occurred during flight (ref. 46). The difficulty was attributed to the clogging of a fuel line by a lump of magnesium paste.

Some of the data from these tests are listed in table I, which shows that, as expected, the fuel-weight specific impulse of magnesium slurry was lower and the fuel-volume specific impulse was greater than obtainable with ethylene in similar vehicles.

TABLE I.—PERFORMANCE OF RAMJET TEST VEHICLES
FUELED WITH MAGNESIUM SLURRY AND ETHYLENE

	First test, single engine (ref. 44) (a)	Second test, twin engine (ref. 46) (b)	Third test, single engine (ref. 45) (c)	Ethylene fuel in twin engine (refs. 40 and 48)
Fuel-weight specific impulse, sec[d]	549	---	770	961; 1059
Fuel-volume specific impulse, lb-sec/ cu ft[d]	e 37,000	---	e 51,800	f 17,500; 19,300
Maximum air specific impulse, sec	151	---	150	------
Acceleration, g ------	4.6	---	6.1	4.13; 3.6
Maximum gross-thrust coefficient	0.658	0.664	0.760	0.885

a Slurry consisted of 50 percent 1.5-micron magnesium, 50 percent JP-4. Brookfield apparent viscosity, 6800 centipoises.
b Slurry consisted of 50.7 percent 0.6-micron magnesium, 49.3 percent JP-4. Brookfield apparent viscosity, approx. 8000 centipoises.
c Slurry consisted of 52.4 percent 1-micron (max.) magnesium, 47.1 percent JP-4, and 0.5 percent surface-active additive.
d Fuel specific impulses are based on gross thrust and hence are not directly comparable with those shown in figure 31.
e Calculated from fuel-weight specific impulse and density of slurry. Density of slurry calculated from specific gravity 1.08 given in ref. 44.
f Calculated from fuel-weight specific impulse and density of compressed ethylene. Density of ethylene calculated from data in ref. 48.

FUEL SYSTEMS FOR EXPERIMENTAL COMBUSTION OF SLURRY FUELS

The unique physical properties of slurries have created many problems that must be considered by designers of handling devices such as pumps, meters, valves, or injectors (ref. 47). The following are several problems faced in the design of slurry-fuel systems:

(1) Metal particles tend to clog passageways and orifices even though the openings may be considerably larger than the maximum particle size. Slurries of milled magnesium powder are more prone to clog constrictions in fuel lines than are slurries of atomized metal powder. Flow restriction caused by this kind of clogging is often progressive and does not always result in complete flow blockage. The effect may be intermittent so that the flow rate and pressure will vary unpredictably.

(2) Metal particles will adhere to valve seats unless one of the surfaces is of rubber or the mating surfaces are wiped clean before contact as in tight-fitting plug valves.

(3) Metal particles tend to enter clearance space between sliding and rotating surfaces. As the parts move, the particles become wedged in and weld to the surface until the mechanism jams.

(4) If the ambient temperature reaches the boiling point of the carrier fluid, a hard, impermeable cake of dry powder can form. This type of clogging, which is most likely to occur when the fuel flow is interrupted for a period of time, is due to fuel drying and is found most frequently in injection nozzles or adjacent piping. These parts are exposed to radiation from the flame zone or are often in a stream of preheated combustion air. The attachment of nozzles and piping to duct walls and combustors results in additional heating by conduction.

In order to overcome these difficulties, it has been necessary to evaluate certain types of equipment to determine whether the fuel systems are satisfactory for use with slurry fuels. In some cases, existing commercial equipment has been adapted for this purpose, and in other cases custom-built equipment has been utilized. The following sections describe some of the experiences encountered in the use of this equipment.

PUMPS

Initial attempts to use gear pumps for aluminum slurries or screw-type, positive displacement, all-steel pumps for magnesium slurry failed because the all-metal parts seized immediately. Later, pumps that could handle magnesium slurry for limited periods were obtained.

A 0.26-gpm/100-rpm screw-type pump could be operated for more than 5 hours when constructed with a tool-steel rotor and a rubber stator. It pumped magnesium slurry at 700 to 800 rpm and a discharge pressure of 200 to 250 pounds per square inch in the recirculating-fuel system described in reference 27. The slurry was made with JP-3 fuel containing only 10 percent aromatics in order to minimize swelling of the rubber. A more solvent-resistant rubber stator could probably have been used.

An air-turbine-driven centrifugal fuel booster pump with an aluminum impeller delivered 180 pounds of magnesium slurry per minute at 300 pounds per square inch before slurry began to leak past the seal and into the bearings. The bearings seized after 17 hours of total running time. Excessively thick slurries that cavitated at the inlet and permitted the pump to overspeed also caused bearing failure. There was no evidence of abrasion of the impeller.

A vertical centrifugal pump of NACA design (fig. 32) also suffered bearing failure (ref. 47). The 6-inch-diameter impeller developed an outlet pressure of 70 pounds per square inch when driven at 3600 rpm by a geared 2.5-horsepower air motor. Even though the slurry level was kept well below the seal, slurry invariably penetrated the seal and damaged the bearings. It appears that centrifugal pumps might continue to operate for long periods if pressurized lubricant were used to prevent seepage of slurry past the seal.

DISPLACEMENT SYSTEMS

Diagrams of three systems for pumping slurries by displacement with a hydraulic fluid are shown in figure 33. Jet fuel was used as the pumping medium and to flush the slurry system after a test run.

In small-diameter systems with tight-fitting pistons (figs. 33 (a) and (b)), if leakage occurred around the pistons during pumping of very viscous slurries, the jet fuel channeled through the slurry and flowed directly to the discharge, mixing only slightly with the slurry. The cylinders in figure 33 (a) (also ref. 30) had an inside diameter of 5 inches. On the piston were two ¼-inch-thick O-rings of 5⅛-inch outside diameter. The jet fuel caused the O-rings to swell. Excessive swelling over a period of time will cause piston seizure.

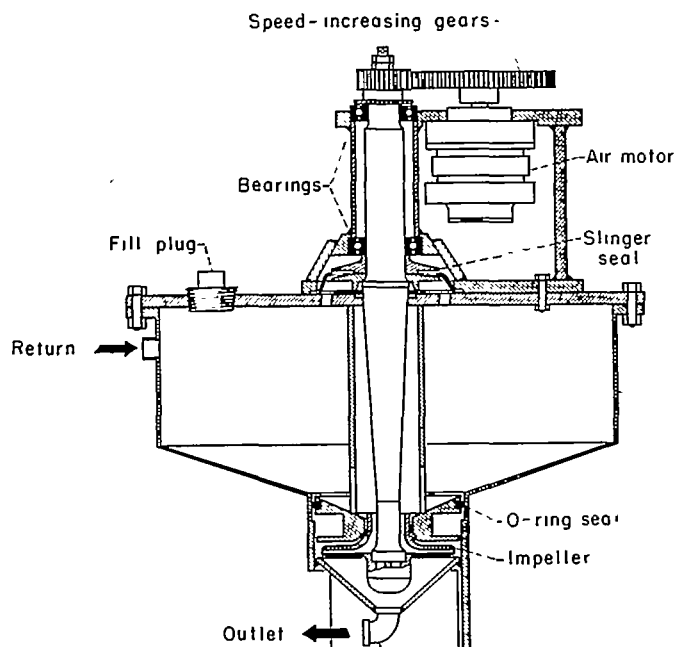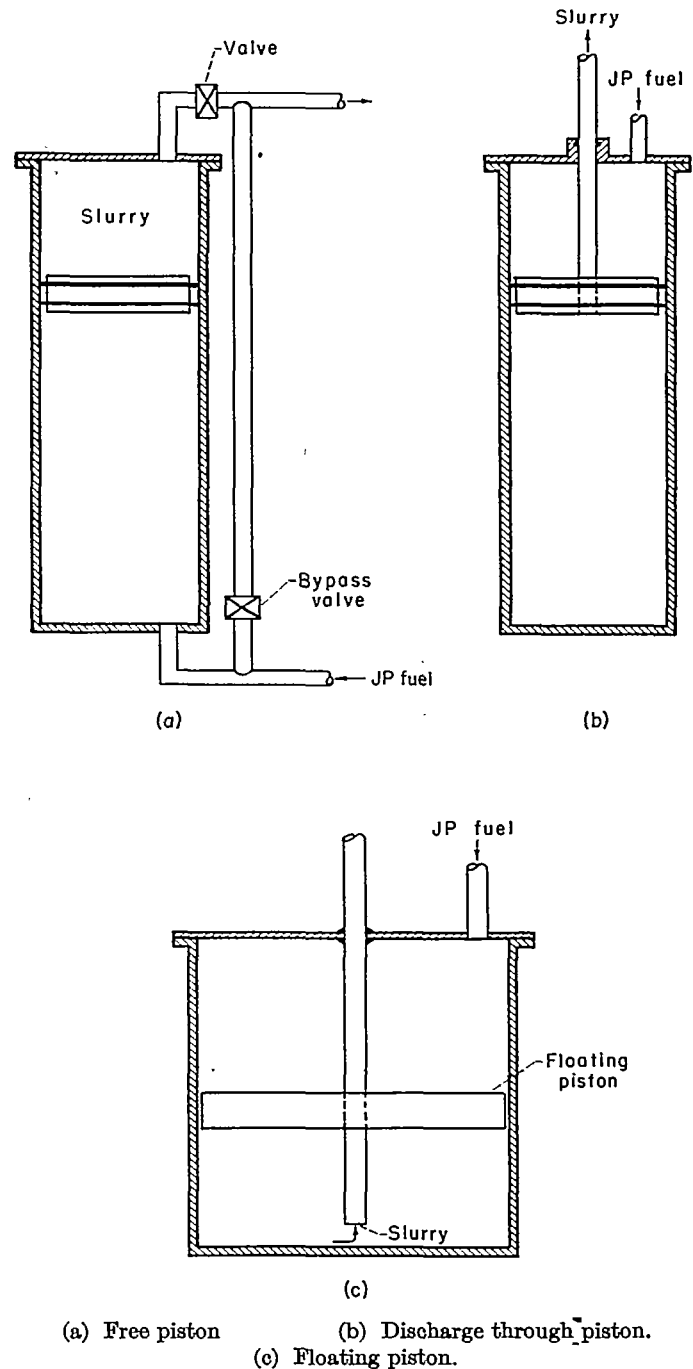Experience showed that in large-diameter (approx. 36-in.)

FIGURE 32.—Vertical centrifugal slurry pump (ref. 47).

(a) Free piston (b) Discharge through piston.
(c) Floating piston.

FIGURE 33.—Slurry displacement systems (ref. 47).

systems with loosely fitting pistons, channelling of the jet fuel through the slurry was not a problem. Figure 33 (c) illustrates such a piston, which is actually a wooden disk of such density that it floated between the slurry and the jet fuel. The displacement systems were not suitable for unstable slurries, since none of them provided for recirculation or agitation of the slurry.

Preliminary work has been done on a displacement system in which Cordite is used as a source of high-pressure gas to propel the piston. This system was used in the flight tests of ramjet vehicles. Design and performance data on such a system are given in reference 44.

VALVES FOR SLURRY SYSTEMS

The problem of finding suitable valves for slurries was not so imposing as the development of suitable pumping equipment. Spring-loaded plug valves with manual or mechanically linked shutoff have been used successfully. These valves, which may be obtained with two-, three-, or four-way bodies, did not leak at a pressure of 125 pounds per square inch and were not damaged by magnesium particles. Unfortunately, however, such valves do not permit fine regulation of flow.

For flow regulation, commercially available valves with rubber membranes that can be moved to vary the flow-passage opening were used. Positive shutoff is reliable because the rubber can close tightly over the metal particles that are trapped on the closure or valve-seating surfaces.
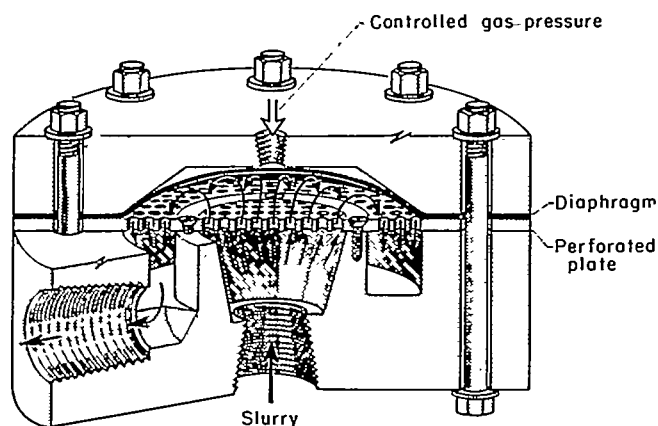
Also, the membrane seals the sliding metal valve parts from contact with the slurry.

The pressure-relief valve shown in figure 34 was used in the recirculating-fuel system described in reference 27. Operation with this valve was entirely satisfactory.

FLOW AND PRESSURE MEASUREMENT

The physical and hydraulic properties of slurries that affect flow and pressure measurement are discussed in appendix B of reference 47. Sharp-edged orifices and Venturi tubes can be used to meter slurries, but the success of such devices depends on the development of pressure gages that will not be affected by solid particles. Ordinary gages have Bourdon tubes, bellows, or diaphragm chambers that contain stagnant zones in which slurries may settle. The resulting sediment impedes the motion of the indicating linkage and is extremely difficult to remove.

In order to avoid these difficulties, several methods have been used to provide for an indirect measurement of slurry flow. For the displacement pumping systems described previously (fig. 33), the jet fuel is metered and the slurry flow rate is determined from the ratio of the densities of the slurry and jet fuel.

FIGURE 34.—Pressure-relief valve (ref. 47).
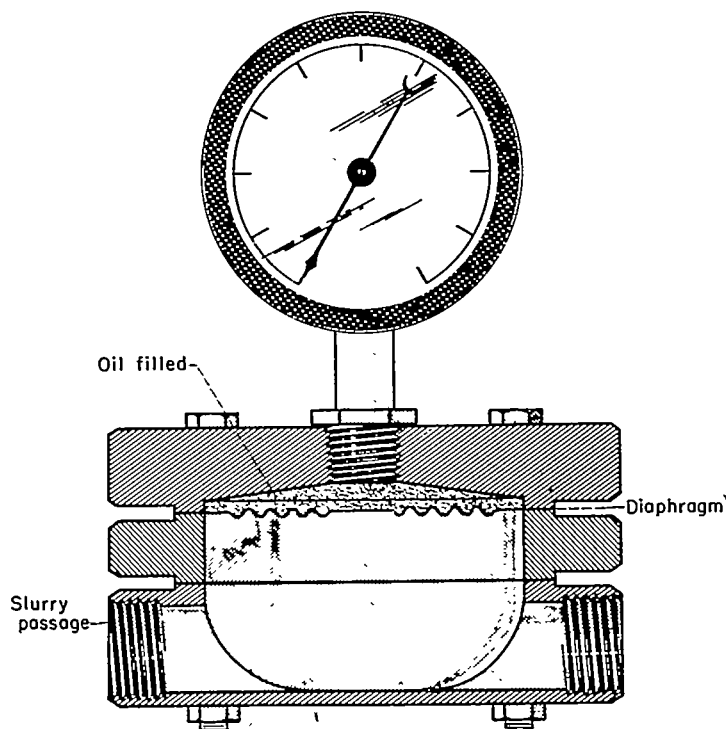
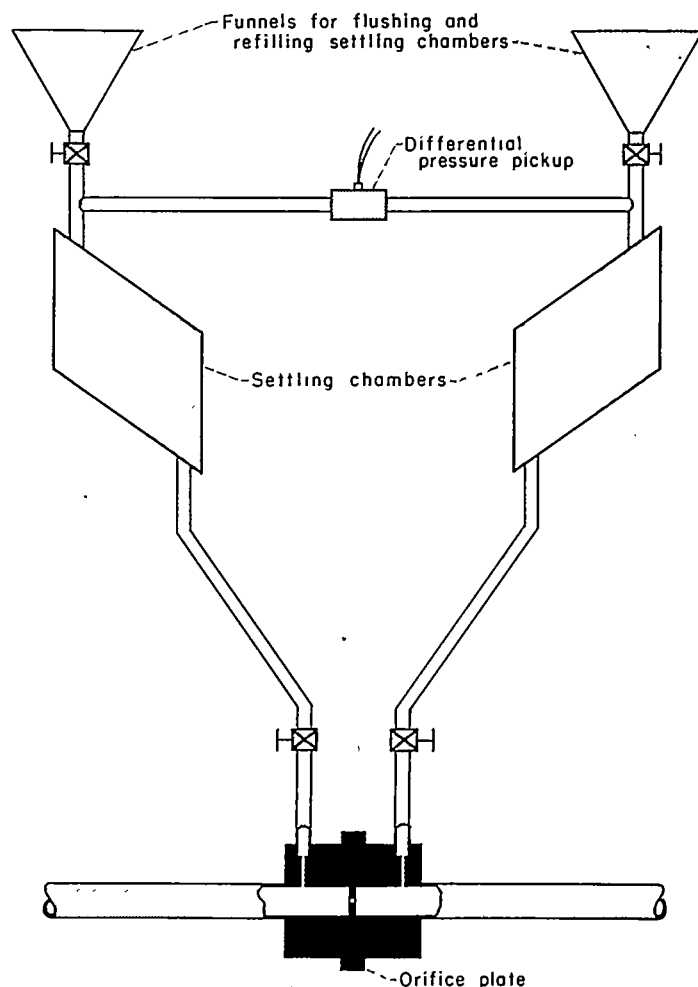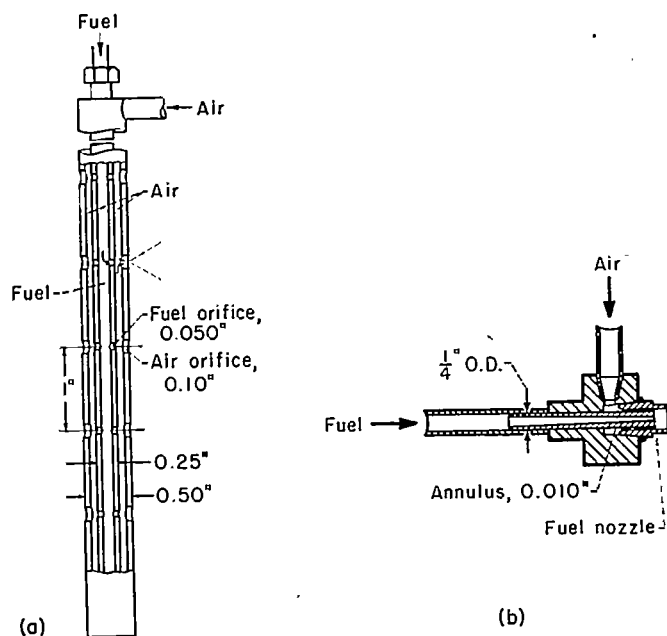
FIGURE 35.—Diaphragm-sealed pressure gage (ref. 47).

FIGURE 36.—Settling chambers for differential pressure gage (ref. 47).

The slurry fuel system described in reference 41 had a fuel tank suspended from a strain gage connected to a strip-chart recorder that plotted fuel weight as a function of time. This type of setup is suitable for tests run at nearly constant fuel-flow rates.

A rotating-vane flowmeter was used in the investigation reported in reference 42. A permanent magnet in the rotor generated an alternating potential having a frequency proportional to the flow. The meter was modified by the manufacturer to incorporate additional clearance in the bearings and bleed holes for continuously flushing the bearings. The slurry passed through this meter at a rate of 0.275 to 0.8 pound per second. The inside diameter of the meter was ⅜ inch. A smaller-size meter clogged with a 50 percent magnesium slurry.

(a) Aspirating spray bar. (b) Air-atomizing nozzle.

FIGURE 37.—Air-atomizing devices for slurry fuels (refs. 27 and 30).

Pressures in slurry fuel-flow systems have been measured by means of diaphragm-sealed pressure gages. As indicated in figure 35, the slurry is not in contact with the pressure-measuring instrument. The pressure of the slurry acting on the diaphragm is transmitted to the gage.

Differential pressures across the orifices or Venturi flowmeters are usually measured by remote-indicating diaphragm-actuated pressure pickups, such as the arrangement described in reference 27. The pickup is protected by a series of settling chambers (fig. 36) filled with jet fuel, which has a lower density than the slurry. Flushing the chambers between tests prevented the slurry from entering the pressure pickup.

SLURRY FUEL INJECTORS

The creation of a homogeneous fuel-air mixture at the entrance to a combustor flame-seating zone is one of the requirements of good combustor design. In turbojet afterburners the duct length available for fuel-air mixing before

the flameholders is severely limited by weight and size considerations.

In the case of slurry fuels, the problem of obtaining a homogeneous mixture at the flame seat is further complicated by the extremely viscous nature of the slurry, which tends to promote coarse atomization and uneven fuel-spray distribution. High-speed photographs of slurry sprays (fig. 12 and refs. 27 and 29) illustrate the magnitude of the droplet-size difference between conventional and slurry fuels and indicate that spray patterns and distribution of gelled magnesium slurry are influenced by slurry viscosity. Other
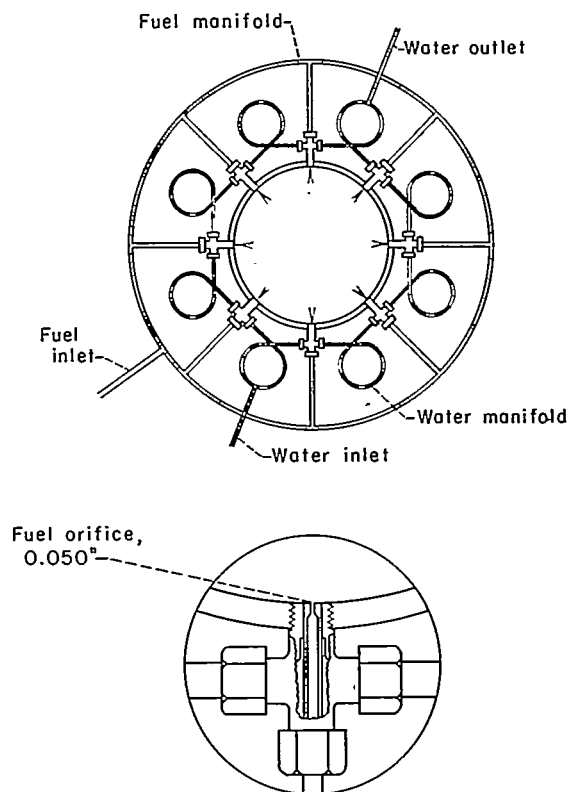

FIGURE 38.—Water-jacketed fuel injector (ref. 27).

tests (ref. 27) indicated that air could be used to promote better atomization. Details of air-atomizing nozzles that have been used successfully are shown in figure 37 (also refs. 27 and 30).

With nozzles of the air-atomizing type, the airstream shields the slurry from the high temperatures of the combustion zone and atomizes the fuel. If the atomizing-air supply is shut off after the slurry flow is interrupted and before the combustor has cooled, the jet-fuel carrier in the slurry quickly boils off and leaves a hard plug of dried powder clogging the injector. When fuel is injected without air atomization, it is often necessary to provide a means of cooling the fuel injector. A water-jacketed slurry injector is illustrated in figure 38 (also ref. 27). Water-cooling may be unnecessary, however, if the slurry injection is preceded by jet-fuel injection. The jet fuel cools the injector; and, if slurry is introduced at a high flow rate, the injector remains cool. Slurry injection may be followed by jet-fuel flow to flush the injector.
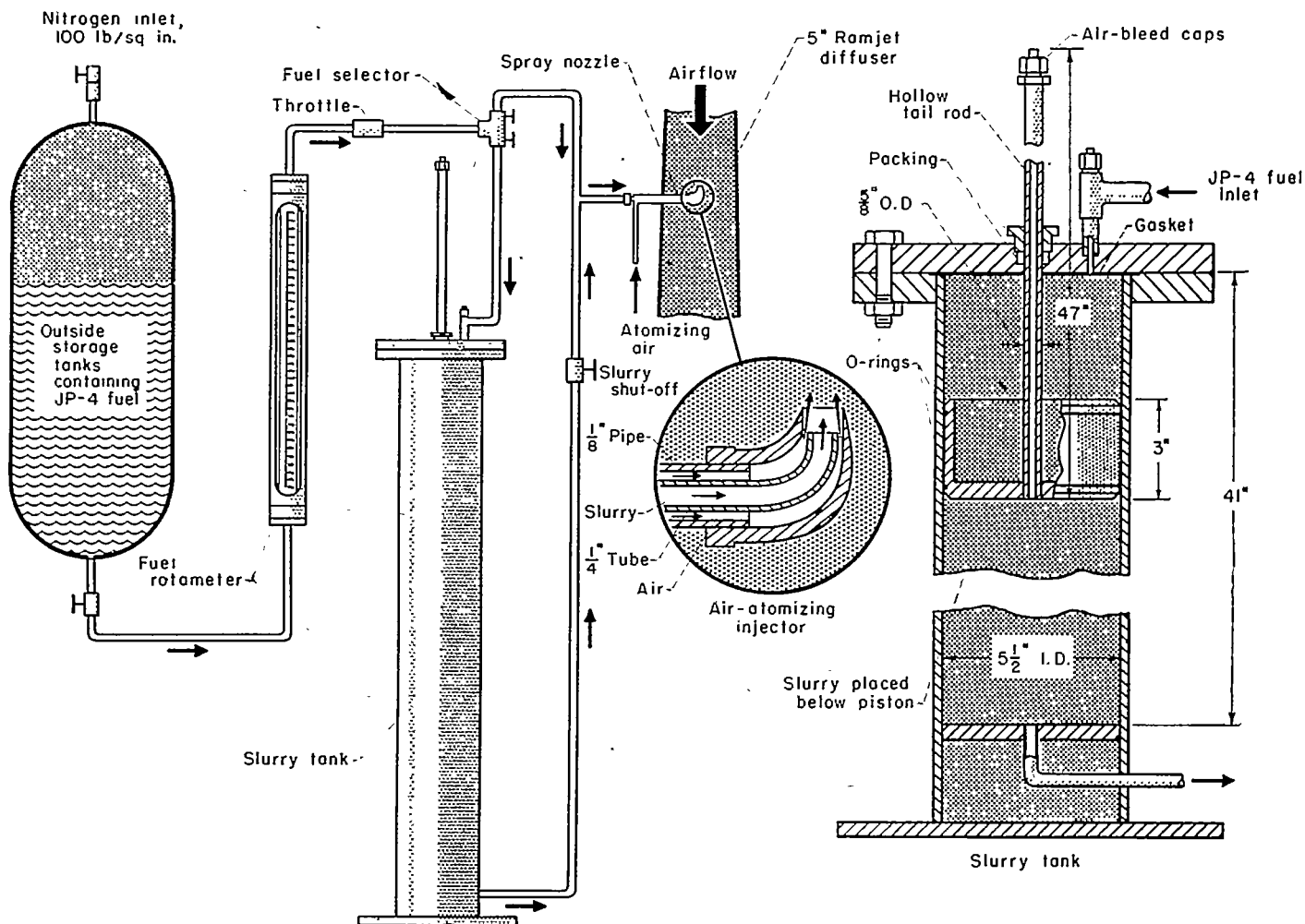
FIGURE 39.—Diagram of fuel system used in conjunction with 5-inch-diameter ramjet burner for tests on boron slurry (ref. 33).
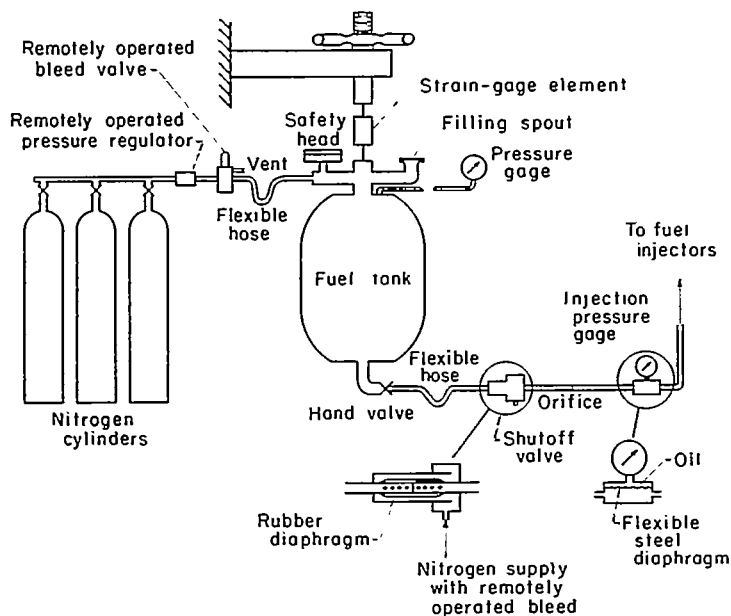

FIGURE 40.—Diagram of fuel system used in conjunction with 6.5-inch-diameter ramjet engine for tests on magnesium slurry (ref. 41).
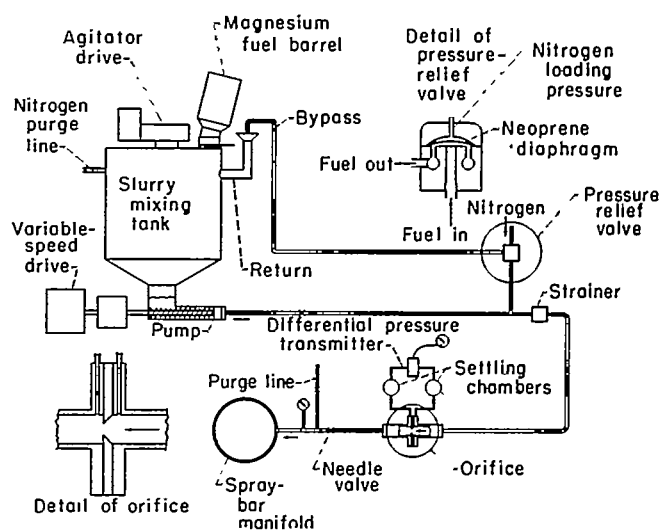

FIGURE 41.—Diagram of afterburner fuel system used for tests of magnesium slurry (ref. 27).

Slurries have been atomized by being impinged on a splash plate or sleeve mounted in the airstream (ref. 41).

Examples of ways the various elements of fuel systems have been combined are shown in figures 39 to 41 and are discussed in some detail in references 27, 41, 42, and 45. Figures 39 and 40 illustrate the transfer of slurries to ramjet engines by displacement with pressurized JP–4 and nitrogen, respectively. Figure 41 shows the use of a pump to force slurry into an afterburner. All these systems, having been designed to operate on the ground and to yield a maximum of operational data, were too heavy and bulky to be usable in aircraft, but probably could be modified for this purpose. The gas-generator pressurized systems used in the Pilotless Aircraft Research Station tests are examples of displacement systems designed for small flight vehicles. Considerably more work would be required to design slurry fuel systems for large flight vehicles.

CONCLUDING REMARKS

The results of the research program indicate that boron-slurry fuels were not satisfactory for use in afterburners and ramjet engines because of the poor combustion efficiency of the boron. Magnesium-slurry fuels performed successfully but can only provide greater thrust than conventional hydrocarbon fuels, not increased range. The flow and combustion characteristics of magnesium slurry necessitated some modifications in conventional fuel systems and combustors. Toward the end of the slurry-fuel program, attention was turned to liquid nonhydrocarbon fuels that were under study and that offered more satisfactory handling characteristics than did magnesium slurry, as well as greater thrust and range than obtainable from hydrocarbons. Consequently, the slurry-fuel program was terminated.

The information obtained on the preparation, flow properties, and stability of concentrated suspensions of boron and magnesium in hydrocarbon may be applicable to the use of suspensions for other purposes.

LEWIS FLIGHT PROPULSION LABORATORY

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

CLEVELAND, OHIO, *August 15, 1958*

REFERENCES

1. Olson, Walter T., and Gibbons, Louis C.: Status of Combustion Research on High-Energy Fuels for Ram Jets. NACA RM E51D23, 1951.
2. Olson, Walter T., and Breitwieser, Roland: NACA Research on Slurry Fuels Through 1954. NACA RM E55B14, 1955.
3. Olson, Walter T.: Possibilities and Problems of Some High Energy Fuels for Aircraft. Paper 41B, SAE Nat. Aero. Meeting (NY), April 1958.
4. Henneberry, Hugh M.: Effect of Fuel Density and Heating Value on Ram-Jet Airplane Range. NACA RM E51L21, 1952.
5. Tower, Leonard K.: Analytic Evaluation of Effect of Inlet-Air Temperature and Combustion Pressure on Combustion Performance of Boron Slurries and Blends of Pentaborane in Octene-1. NACA RM E55A31, 1955.
6. Tower, Leonard K.: Analytic Evaluation of Effect of Inlet-Air Temperature and Combustion Pressure on Combustion Performance of Boron Slurries and Blends of Pentaborane in Octene-1. Supplement I—Influence of New Boric-Oxide Vapor-Pressure Data on Calculated Performance of Pentaborane. NACA RM E56D02, 1956.
7. Tower, Leonard K., Breitwieser, Roland, and Gammon, Benson E.: Theoretical Combustion Performance of Several High-Energy Fuels for Ramjet Engines. NACA Rep. 1362, 1958. (Supersedes NACA RM's E51C12, E51C23, E51D25, E51F05, E52L08, and E53G14.)
8. Branstetter, J. Robert, Lord, Albert M., and Gerstein, Melvin: Combustion Properties of Aluminum as Ram-Jet Fuel. NACA RM E51B02, 1951.
9. Pinns, Murray L.: Effect of Surface-Active Additives on the Physical Behavior of 50-Percent Slurries of 1.5-Micron Magnesium in n-Decane. NACA RM E54K22a, 1955.
10. Weltmann, Ruth N., and Kuhns, Perry W.: An Automatic Viscometer for Non-Newtonian Materials. NACA TN 3510, 1955.
11. Pinns, Murray L., and Goodman, Irving A.: Study of the Physical Properties of Petrolatum-Stabilized Magnesium-Hydrocarbon Slurry Fuels. NACA RM E53J16, 1954.
12. Altshuller, Aubrey P.: Some Dielectric Properties of Suspensions of Boron Powders in Mineral Oil. NACA RM E55F02, 1955.
13. Altshuller, Aubrey P.: The Shapes of Particles from Dielectric Constant Studies of Suspensions. Jour. Phys. Chem., vol. 58, no. 7, July 1954, pp. 544–547.
14. Altshuller, Aubrey P.: Study of Some Dielectric Properties of Suspensions of Magnesium Particles in Mineral Oil. NACA RM E53L09, 1954.
15. Goodman, Irving A., and Fenn, Virginia O.: Preparation and Properties of Concentrated Boron-Hydrocarbon Slurry Fuels. NACA RM E54F18a, 1954.
16. Goodman, Irving A., and Fenn, Virginia O.: Preparation of 50 Percent Boron-Hydrocarbon Slurries Using Combinations of Glycerol Sorbitan Laurate with Various Thickeners. NACA RM E55E17, 1955.
17. Hipsher, Harold F.: Effect of Temperature on Viscosity of Slurries of Boron and Magnesium in JP-5 Fuel. NACA RM E55E19, 1955.
18. Witzke, Walter R., Prok, George M., and Walsh, Thomas J.: A Preliminary Study of the Preparation of Slurry Fuels from Vaporized Magnesium. NACA RM E53K23, 1954.
19. Witzke, Walter R., Prok, George M., and Keller, Thomas A.: Design Considerations of a Condensing System for Vaporized Magnesium. NACA RM E55I20, 1955.
20. Pinns, Murray L.: Estimation of Specific Surface of Finely Divided Magnesium. NACA RM E56D10a, 1956.
21. Pinns, Murray L.: Effect of Surface-Active Additives on Physical Properties of Slurries of Vapor-Process Magnesium. NACA RM E55H26, 1955.
22. Pinns, Murray L.: The Effect of Surface-Active Additives on the Behavior of Magnesium-Decane Slurries. M. S. Thesis, Case Inst. Tech., 1954.
23. Weltmann, Ruth N., and Keller, Thomas A.: Pressure Losses of Titania and Magnesium Slurries in Pipes and Pipeline Transitions. NACA TN 3889, 1957.
24. Prok, George M.: Effect of Plastic Viscosity and Yield Value on Spray Characteristics of Magnesium-Slurry Fuel. NACA RM E56J19a, 1957.
25. Gibbs, James B., and Cook, Preston N., Jr.: Preparation and Physical Properties of Metal Slurry Fuels. NACA RM E52A23, 1952.
26. Caves, Robert M.: Stabilization of 50-Percent Magnesium—JP–4 Slurries with Some Aluminum Soaps of C₈ Acids. NACA RM E54C10, 1954.
27. Tower, Leonard K., and Branstetter, J. Robert: Combustion Performance Evaluation of Magnesium-Hydrocarbon Slurry Blends in a Simulated Tail-Pipe Burner. NACA RM E51C26, 1951.

28. Lamberti, Joseph M.: The Effect of Magnesium Particles of Various Equivalent Diameters on Some Physical Properties of Petrolatum-Stabilized Magnesium-Hydrocarbon Slurries. NACA RM E54A22, 1954.

29. Cook, Preston N., Jr., Evans, Vernida E., and Lezberg, Erwin A.: Experimental Investigation of Physical and Combustion Properties of Several Residual Fuel Oil sand Magnesium—Fuel-Oil Slurries in a Ram-Jet-Type Combustor. NACA RM E53D30, 1953.

30. Cook, Preston N., Jr., Lord, Albert M., and Kaye, Samuel: Blow-Out Velocities of Various Petroleum, Slurry, and Hydride Fuels in a 1⅝-Inch-Diameter Combustor. NACA RM E54A28, 1954.

31. Morris, James F., Caves, Robert M., and Lord, Albert M.: Blow-Out Velocities of Several Slurry and Liquid Fuels in a 1⅝-Inch-Diameter Combustor. NACA RM E54L27a, 1955.

32. Lord, Albert M.: An Experimental Investigation of the Combustion Properties of a Hydrocarbon Fuel and Several Magnesium and Boron Slurries. NACA RM E52B01, 1952.

33. Reynolds, Thaine W., and Haas, Donald P.: Performance of Slurries of 50 Percent Boron in JP-4 Fuel in 5-Inch Ram-Jet Burner. NACA RM E54D07, 1954.

34. Kerslake, William R., Dangle, E. E., and Cervenka, A. J.: Experimental Evaluation of Boron-Hydrocarbon Slurry in a 16-Inch Ram-Jet Combustor. NACA RM E55C07, 1955.

35. Rabinovich, B. V.: Viscosity of Borax and Boric Anhydride in Interval of Softening. Jour. Phys. Chem (U. S. S. R.), vol. 16, 1942, pp. 23–26.

36. Lord, Albert M., and Evans, Vernida E.: Effect of Particle Size and Stabilizing Additives on the Combustion Properties of Magnesium Slurry. NACA RM E52K12, 1953.

37. Coffin, Kenneth P.: Burning Times of Magnesium Ribbons in Various Atmospheres. NACA TN 3332, 1954.

38. Tower, Leonard K.: Effect of Water Vapor on Combustion of Magnesium-Hydrocarbon Slurry Fuels in Small-Scale After-burner. NACA RM E52H25, 1952.

39. Povolny, John H., Useller, James W., and Chelko, Louis J.: Experimental Investigation of Thrust Augmentation of 4000-Pound-Thrust Axial-Flow-Type Turbojet Engine by Interstage Injection of Water-Alcohol Mixtures in Compressor. NACA RM E9K30, 1950.

40. Dettwyler, H. Rudolph, and Bond, Aleck C.: Flight Performance of a Twin-Engine Supersonic Ram Jet from 2,300 to 67,200 Feet Altitude. NACA RM L50L27, 1951.

41. Branstetter, J. Robert, Gibbs, James B., and Kaufman, Warner B.: Magnesium-Slurry Combustion Performance in 6.5-Inch-Diameter Ram-Jet Engine Mounted in Connected-Pipe Facility. NACA RM E53E27, 1953.

42. Gibbs, James B.: Starting Characteristics and Combustion Performance of Magnesium Slurry in 6.5-Inch-Diameter Ram-Jet Engine Mounted in Connected-Pipe Facility. NACA RM E53K05, 1954.

43. Simon, Dorothy M., and Wong, Edgar L.: Flame Velocities over a Wide Composition Range for Pentane-Air, Ethylene-Air, and Propyne-Air Flames. NACA RM E51H09, 1951.

44. Bartlett, Walter A., Jr., and Hagginbothom, William K., Jr.: Flight and Preflight Tests of a Ram Jet Burning Magnesium Slurry Fuel and Utilizing a Solid-Propellant Gas Generator for Fuel Expulsion. NACA RM L55A24, 1955.

45. Bartlett, Walter A., Jr., and Merlet, Charles F.: Flight Investigation of a Ram Jet Burning Magnesium Slurry Fuel and Having a Conical Shock Inlet Designed for a Mach Number of 4.1. NACA RM L56I24a, 1957.

46. Trout, Otto F., Jr., and Kennedy, Thomas L.: Preflight and Flight-Test Investigation of a 50-Percent-Magnesium 50-Percent JP-4 Slurry Fuel in a Twin-Engine Ram-Jet Vehicle. NACA RM L56C06, 1956.

47. Barnett, Henry C., Lord, A. M., and Wise, P. H.: Preparation and Handling of Magnesium-Hydrocarbon Slurries for Jet-Engine Applications. NACA RM E55D01, 1955.

48. Faget, Maxime A., and Dettwyler, H. Rudolph: Initial Flight Investigation of a Twin-Engine Supersonic Ram Jet. NACA RM L50H10, 1950.